Sternentstehung - Star Formation

Winter term 2017/2018

Henrik Beuther & Thomas Henning

17.10 Today: Introduction & Overview (H.B.)
24.10 Physical processes I (H.B.)
31.10 no lecture – Reformationstag
07.11 Physcial processes II (H.B.)
14.11 Molecular clouds as birth places of stars (H.L.)
21.11 Molecular clouds cont., virial & Jeans Analysis (H.B.)
28.11 Collapse models I (H.B.)
05.12 Collapse models II (T.H.)
12.12 Protostellar evolution (T.H.)
19.12 Pre-main sequence evolution & outflows/jets (T.H.)
09.01 Accretion disks I (T.H.)
16.01 Accretion disks II (T.H.)
23.01 High-mass star formation, clusters and the IMF (H.B.)
30.01 Planet formation (T.H.)
06.02 Examination week, no star formation lecture

Book: Stahler & Palla: The Formation of Stars, Wileys

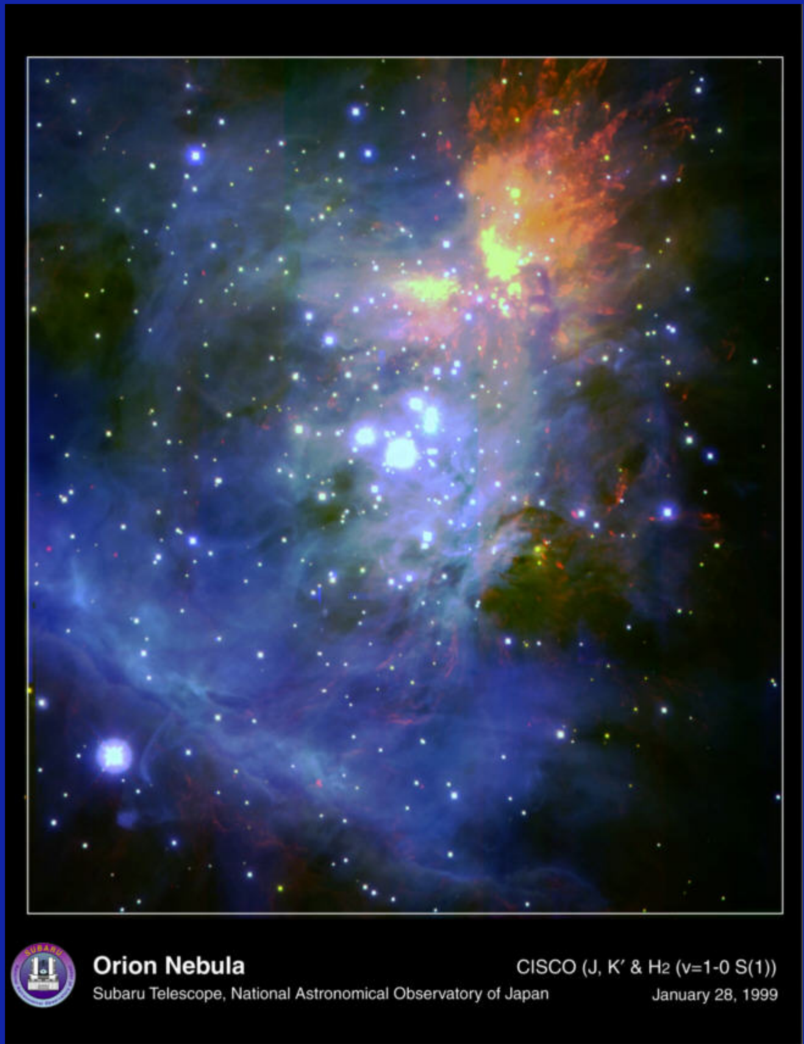
More Information and the current lecture files: http://www.mpia.de/homes/beuther/lecture_ws1718.html

beuther@mpia.de, henning@mpia.de

Topics today

- General concepts of massive star formation
- Outflows in high-mass star-forming regions
- Rotation and disks
- Clusters and the IMF

Massive Star Formation



- Why important?

- Although few in numbers → $L \propto M^3$
- Inject significant amounts of energy into ISM during their lifetime (outflows, radiation, supernovae).
- Produce all the heavy elements.
- Low-mass star formation strongly influenced by massive stars.

- Massive stars exclusively form in clusters.
- Short Kelvin-Helmholtz contraction time:

$$t_{KH} = 3x10^7 \text{ yr } (M_*/1M_s)^2 (R_*/1R_s)^{-1} (L_*/1L_s)^{-1}$$

For $60M_s$, $12R_s$ and $10^{5.9}L_s$ we find:

$t_{KH} \sim 11000$ yr

→ no observable pre-main seq. phase

- Radiation pressure important constraint.

Eddington luminosity and limit

Eddington luminosity: upper luminosity limit before star is unstable.

- *Assumptions: spherical symmetry and fully ionized hydrogen.*
  → Radiation exerts force on free electrons via Thomson scattering:
  $\sigma_T = (q^2/mc^2)^2$ (σ_T: cross sec., q: charge, m: mass)
- Outward radial force equals rate at which electron absorbs momentum:
  $\sigma_T S/c$ (S: energy flux)
  → Radiation pushes out electron-proton pairs against grav. force
  $GM(m_p+m_e)/r^2 \sim GMm_p/r^2$

- With flux $S = L/4\pi r^2$, the force equilibrium is → $GMm_p/r^2 = \sigma_T L/(4\pi r^2 c)$

  → Eddington luminosity: $L_{Edd} = 4\pi GMc\,(m_p/\sigma_T)$ (independent of r)
  $= 4\pi GMc/\kappa$ ($\kappa=\sigma_T/m_p$ mass abs. coefficient)

  → $L_{edd}\,[L_{sun}] = 1.3 \times 10^{38}\,(M/M_{sun})$ erg/s $\sim 3 \times 10^4\,(M/M_{sun})$

- If $L > L_{edd}$ then
  - Accretion stops if L provided by accretion
  - Gas layers pushed out and star unstable if provided by nuclear fusion.
- Scaling relations for massive (proto)stars: $L \propto M^a$ with $2<a<4$

Radiation pressure

- In contrast, now the radiation pressure of the central massive (proto)star on the surrounding dust cocoon. Same relation:

$$L/M = 4\pi Gc/\kappa$$ (κ: mass abs. Coefficient)

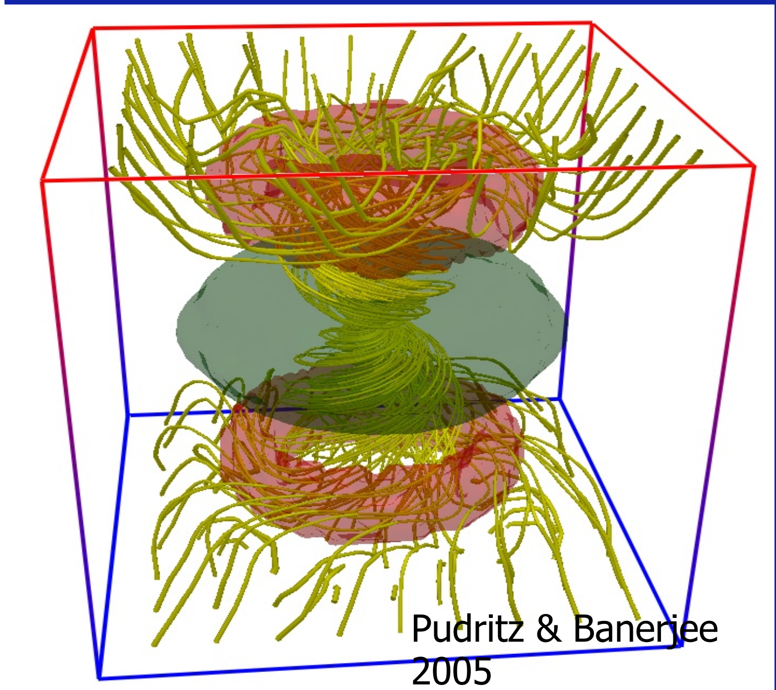
- While κ is very low for ionized H plasma ($\kappa \sim 0.3 cm^2 g^{-1}$), at the dust destruction front (T~1500K) it is considerably larger with $\kappa \sim 10 cm^2 g^{-1}$.

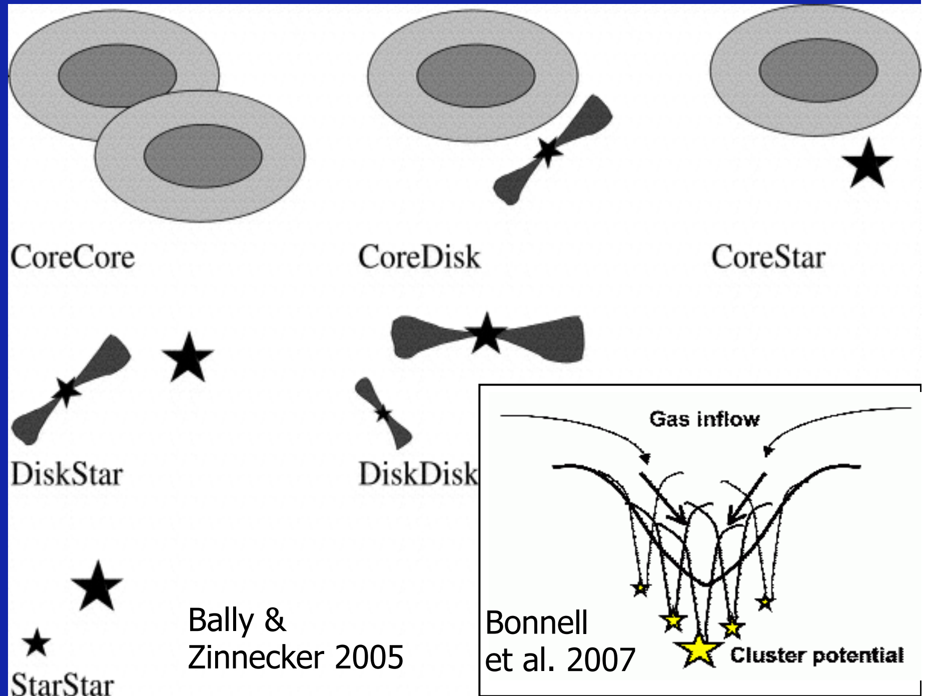
$$\rightarrow \quad L/M \sim 10^3 \ [L_{sun}/M_{sun}]$$

→ In spherical symmetric accretion models, accretion is expected to stop as soon as the luminosity is approximately 1000 times larger than the mass of the protostar. → No problem for low-mass star formation.

→ The critical ratio is reached for stars of approximately $10M_{sun}$. Since more massive stars are know, the assumption of spherical accretion has to be wrong and other processes are needed.

Competing massive star formation scenarios





<u>Modified low-mass star formation:</u>
- Increase accretion rates a few orders of mag.
- 2D disk geometry helps accretion processes.
- Radiation pressure can escape through outflow cavities → flashlight effect

Wolfire & Cassinelli 1987, Jijina & Adams 1996, Yorke & Sonnhalter 2002, Norberg & Maeder 2002, Keto 2002, 2003, McKee & Tan 2002, 2003, Krumholz et al. 2005, 2009, Banerjee & Pudritz 2005, Kuiper et al. 2010, 2011 Tan et al. 2014

<u>Competetive accretion and coalescence:</u>
- Massive stars form only in clusters.
- The cluster potential favours accretion toward objects in the cluster centers.
- All kinds of protostellar entities may merge.

Bonnell et al. 1998, 2004, 2004, 2007, Stahler et al. 2000, Bally & Zinnecker 2005, Zinnecker & Yorke 2007, Bally et al. 2015 …

Turbulent accretion: scaling up low-mass sf

- A $100 M_{sun}$ star forms in $\sim 10^5$ yrs → average accretion rate $\sim 10^{-3} M_{sun}/yr$

- Standard low-mass accretion rate (Shu 1977): $dM/dt \sim c_s^3/G \sim 2 \times 10^{-6} M_{sun}/yr$.

- McKee & Tan (2002, 2003): "turbulent core model": Massive stars form within grav. bound cores supported by turbulence and magnetic fields.

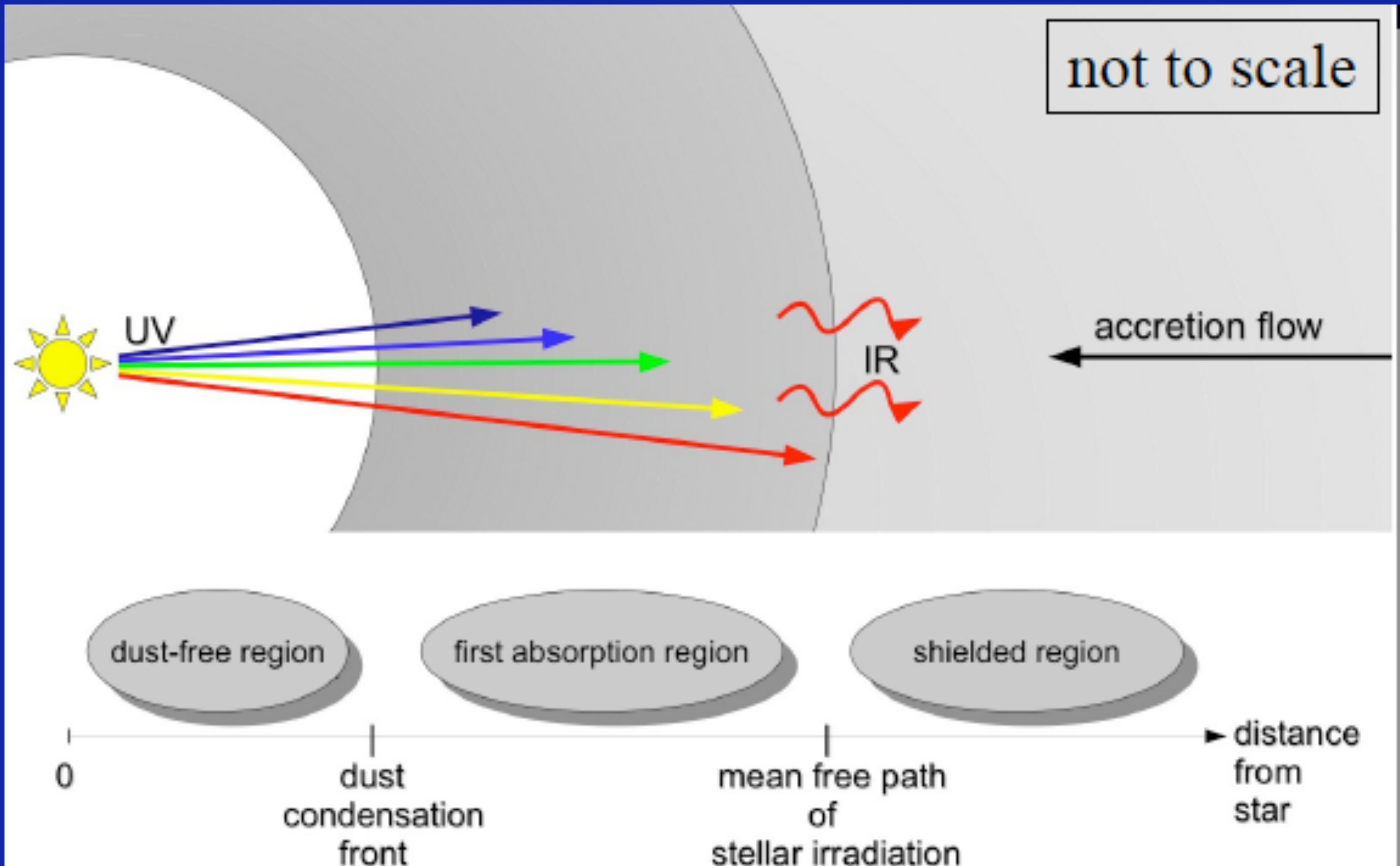
→ The turbulent support raises the sound speed c_s and hence dM/dt.

$$dM/dt \sim 0.5 \times 10^{-3} (M_{final}/30 M_{sun})^{3/4} \Sigma_{cl}^{3/4} (M/M_{final})^{0.5} \quad [M_{sun}/yr]$$

$$t \sim 1.3 \times 10^5 (M_{final}/30 M_{sun})^{1/4} \Sigma_{cl}^{-3/4} \quad [yr]$$

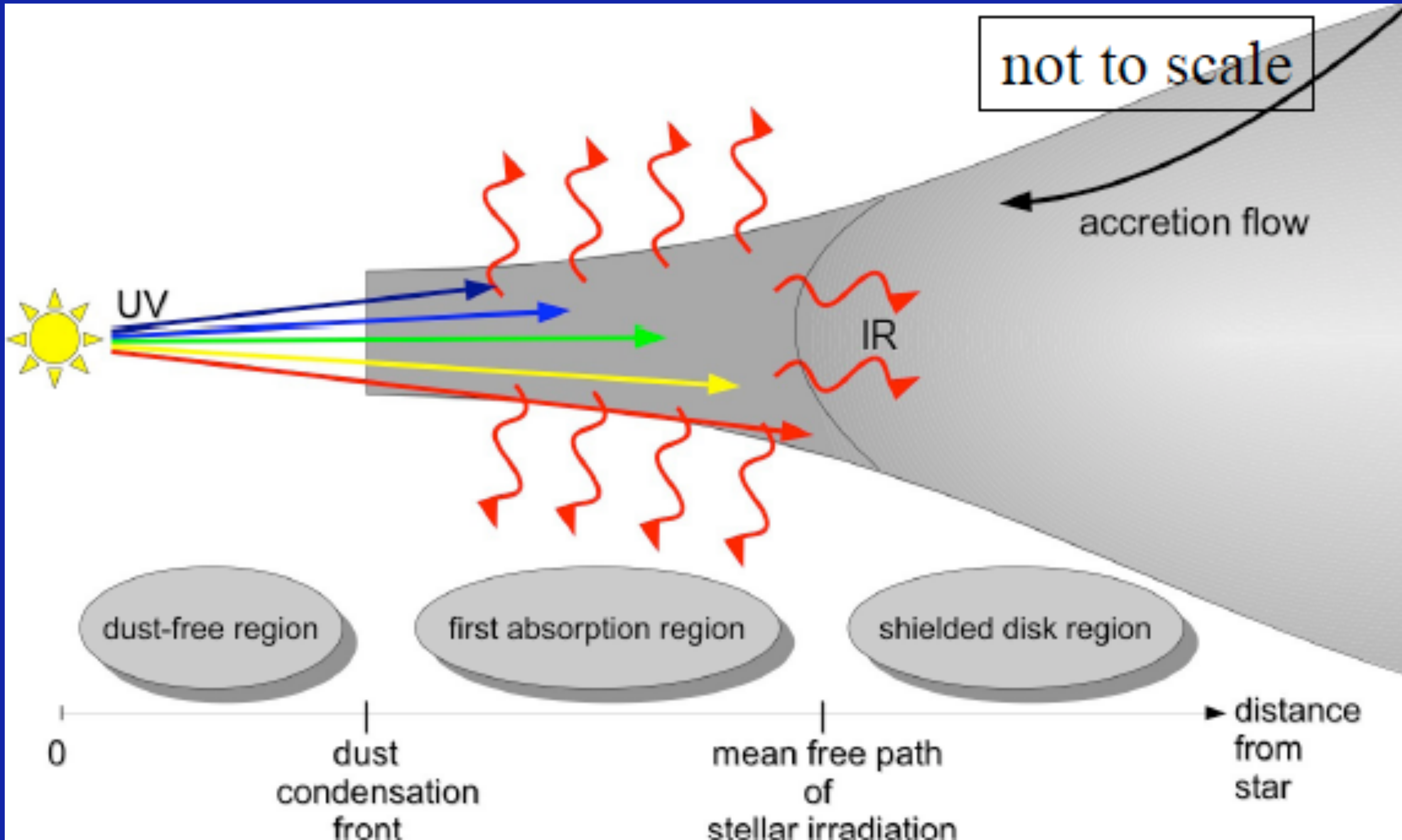
Σ_{cl}: cloud surface density $\sim 1 g\ cm^{-2}$

Radiation pressure in 1D and 2D

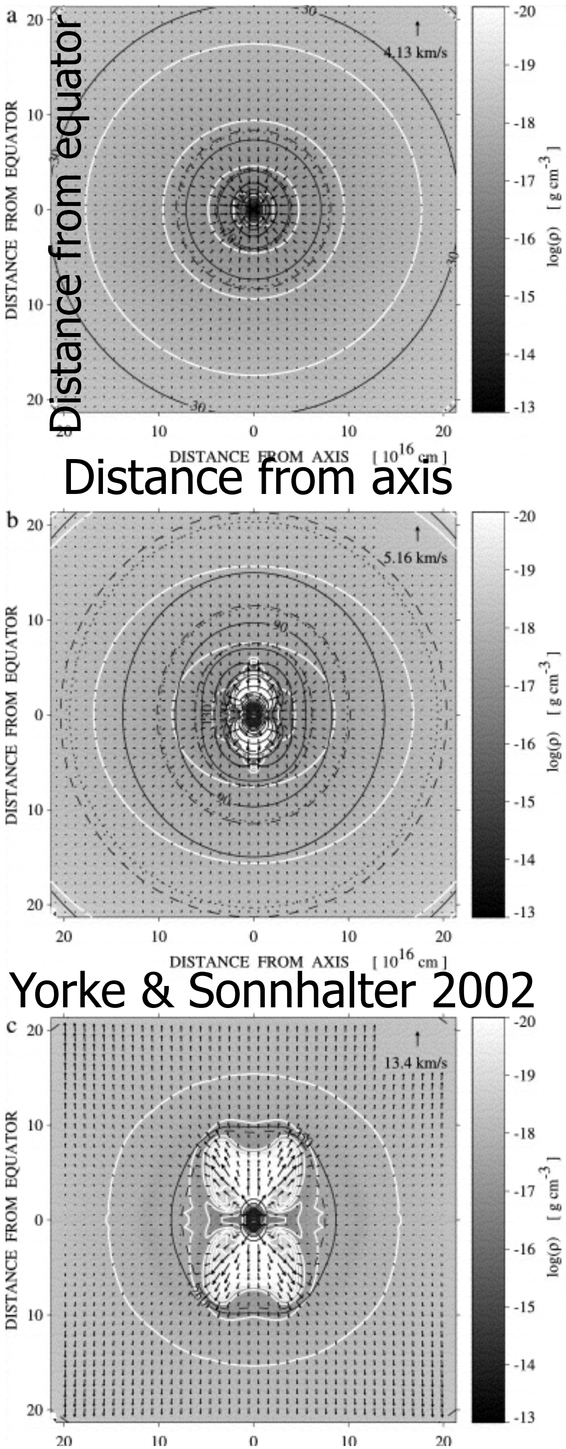


Courtesy of Rolf Kuiper

Radiation pressure in 1D and 2D



Courtesy of Rolf Kuiper



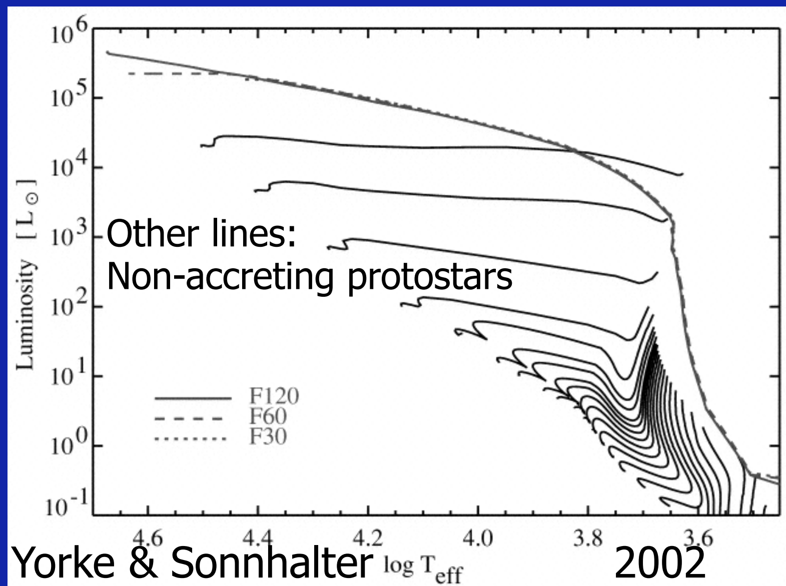
Forming massive accretion disks

2D frequency-dependent hydrodynamic simulations

→ short-wavelength radiation (most effective for radiative acceleration) escapes in polar directions.

→ Radiation driven outflows in polar direction and disks in the equatorial direction are forming.

→ Massive stars may form in a similar fashion as low-mass protostars due to disk accretion.



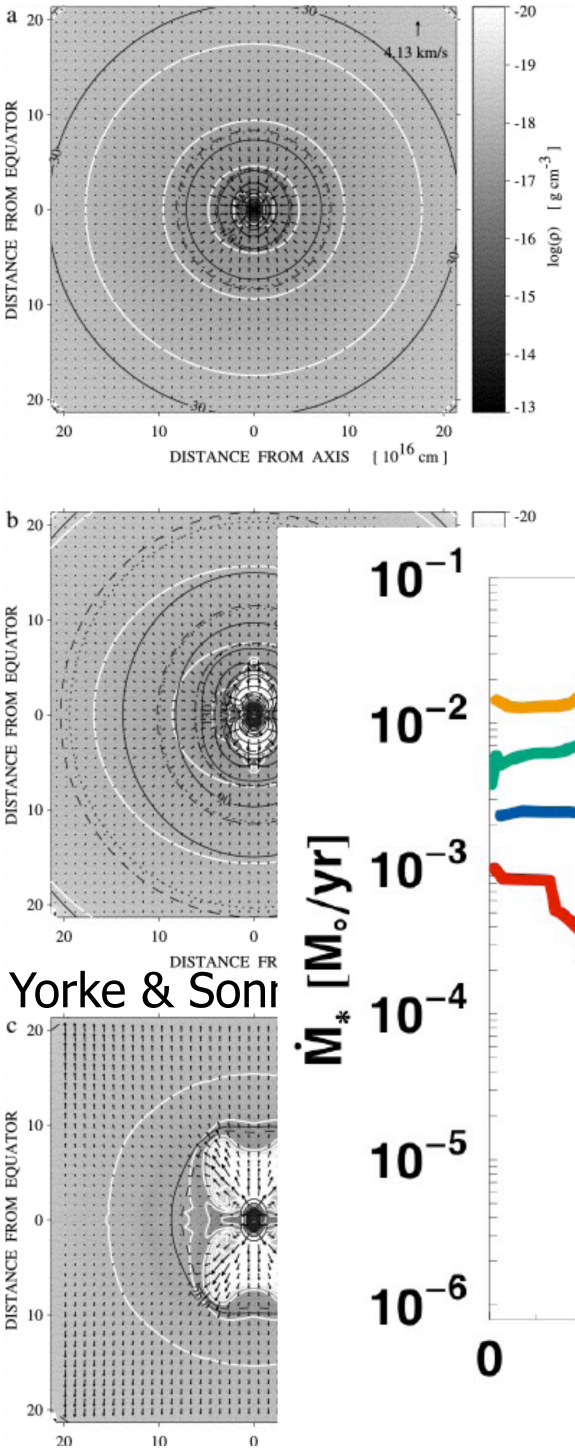
Forming massive accretion disks

2D frequency-dependent hydrodynamic simulations

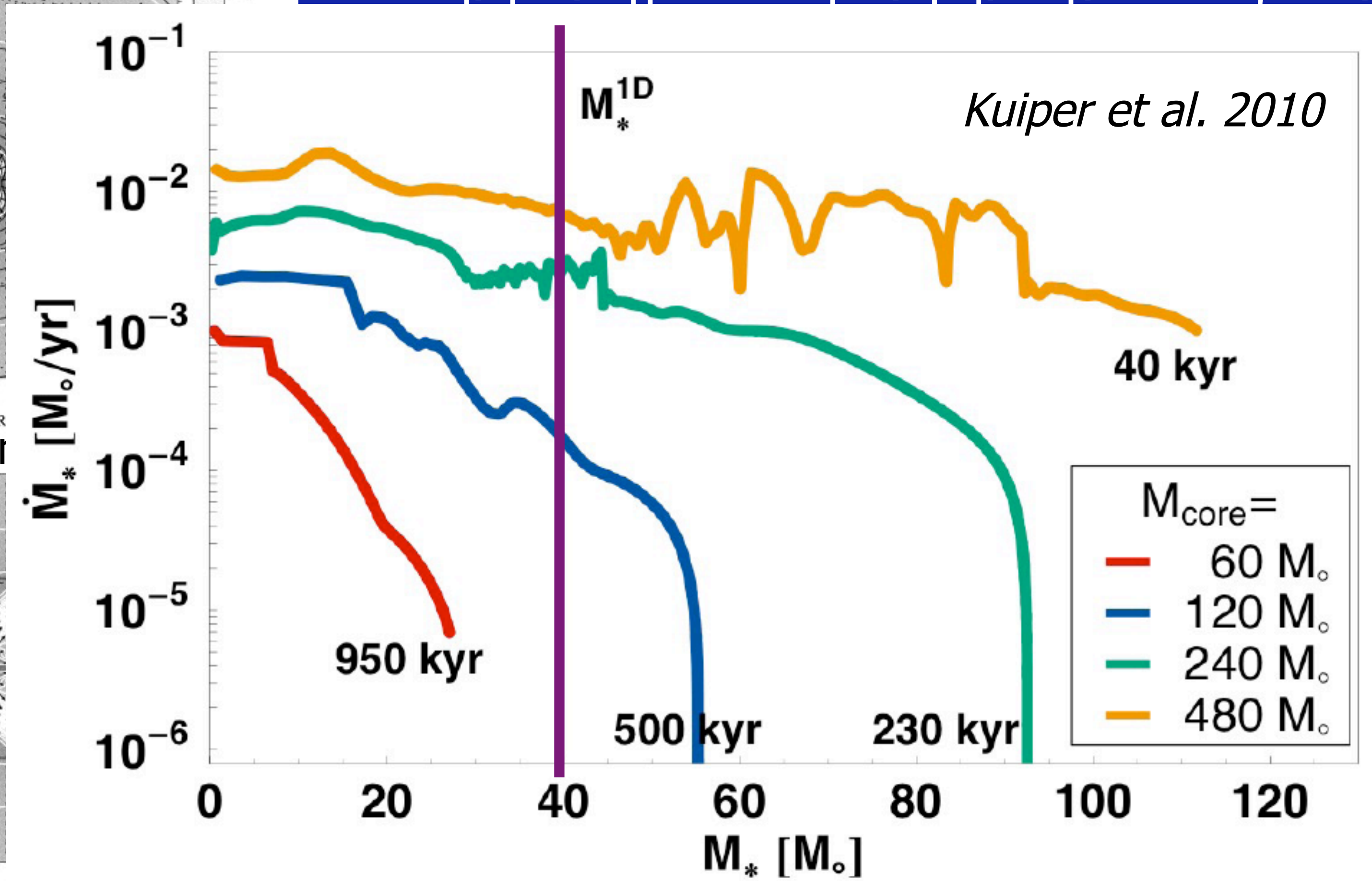
→ short-wavelength radiation (most effective for radiative acceleration) escapes in polar directions.

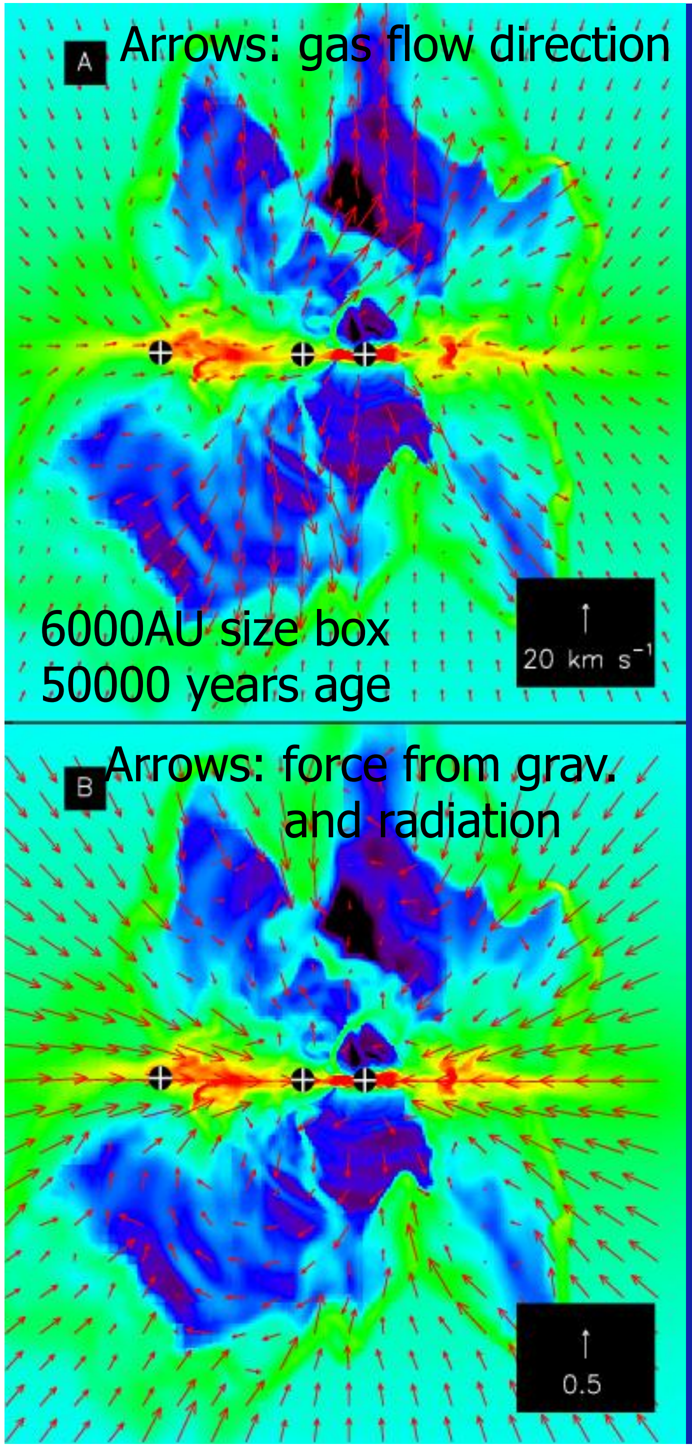
→ Radiation driven outflows in polar direction and ... ing.

... n as



Yorke & Sonn...





3D radiative hydro simulations

- Starting with 100 to 200M_{sun} cores.

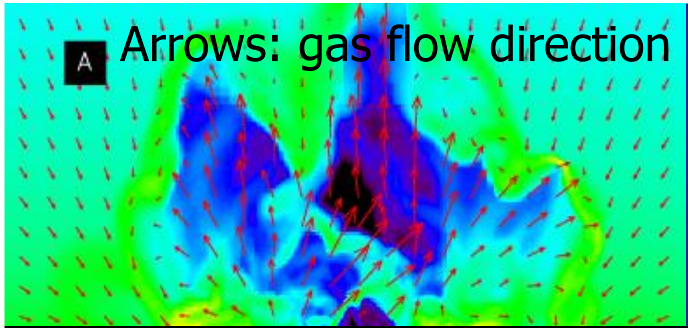
- Until ~17M_{sun} smooth accretion flow.

- Low angular momentum gas accretes directly on protostar, high angular momentum gas forms Keplerian accretion disk.

- From 17M_{sun} upwards, radiation pressure starts driving out gas, bubbles form.
  Further infalling gas moves along the bubble walls and falls onto disk.

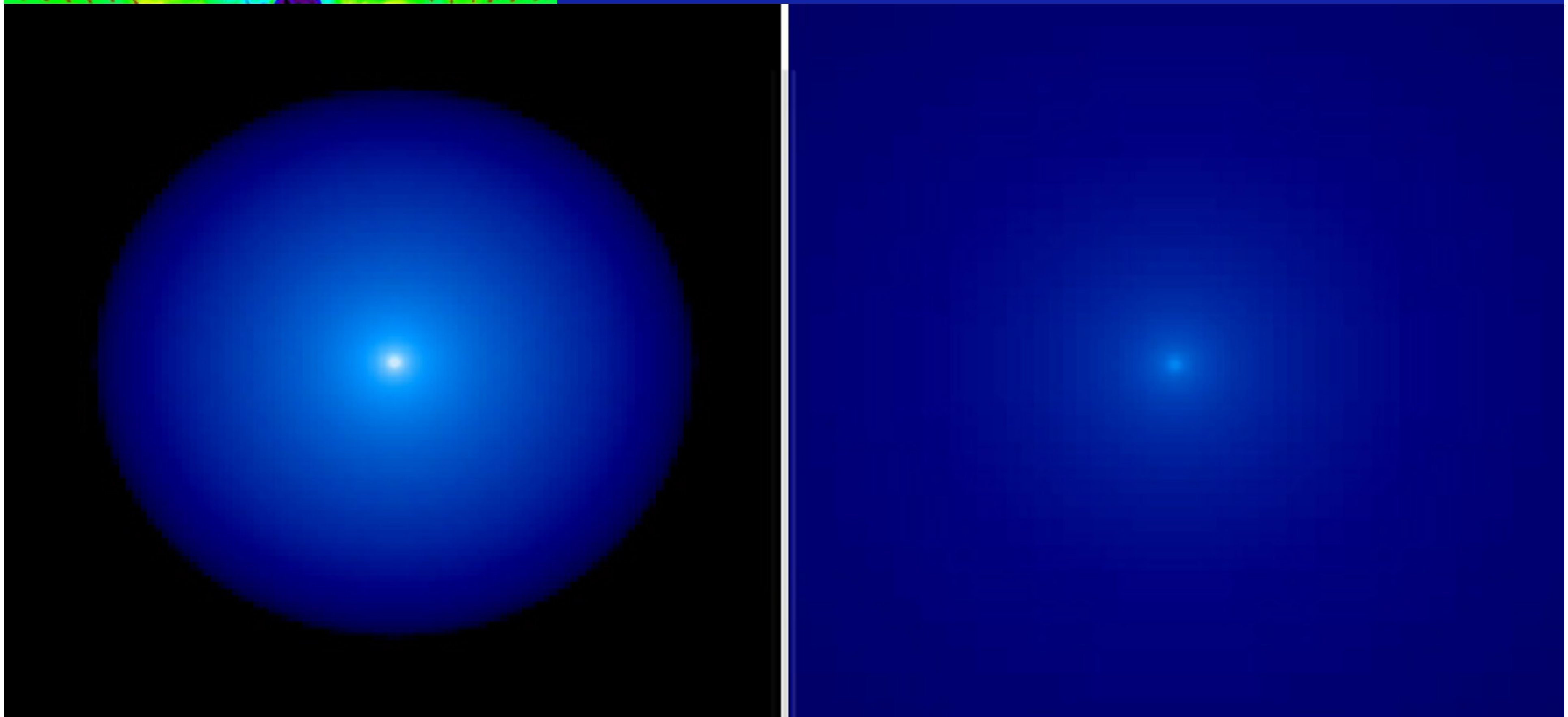
- Disk gravitationally instable forming more stars.

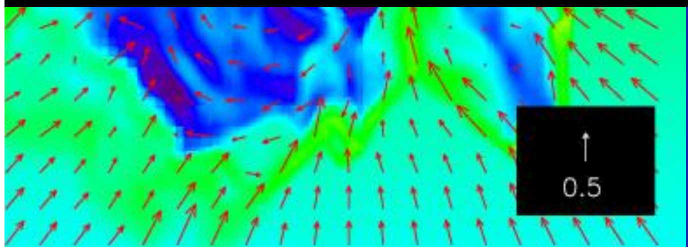
Krumholz et al. 2009



3D radiative hydro simulations

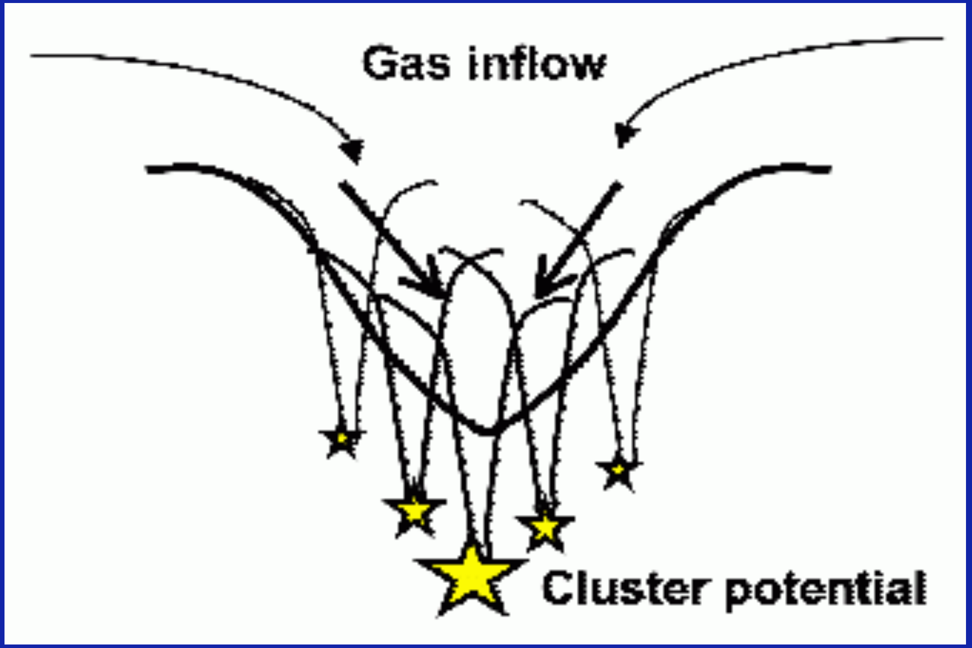
- Starting with 100 to 200M_{sun} cores.





Krumholz et al. 2009

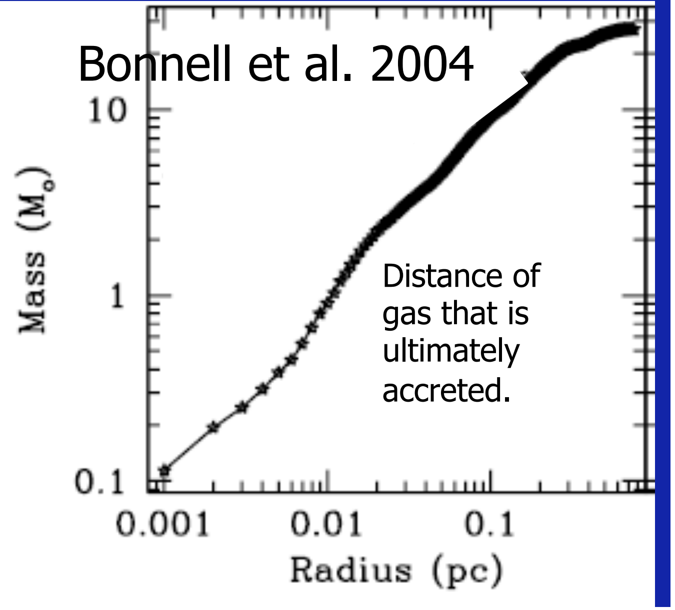
Competetive Accretion



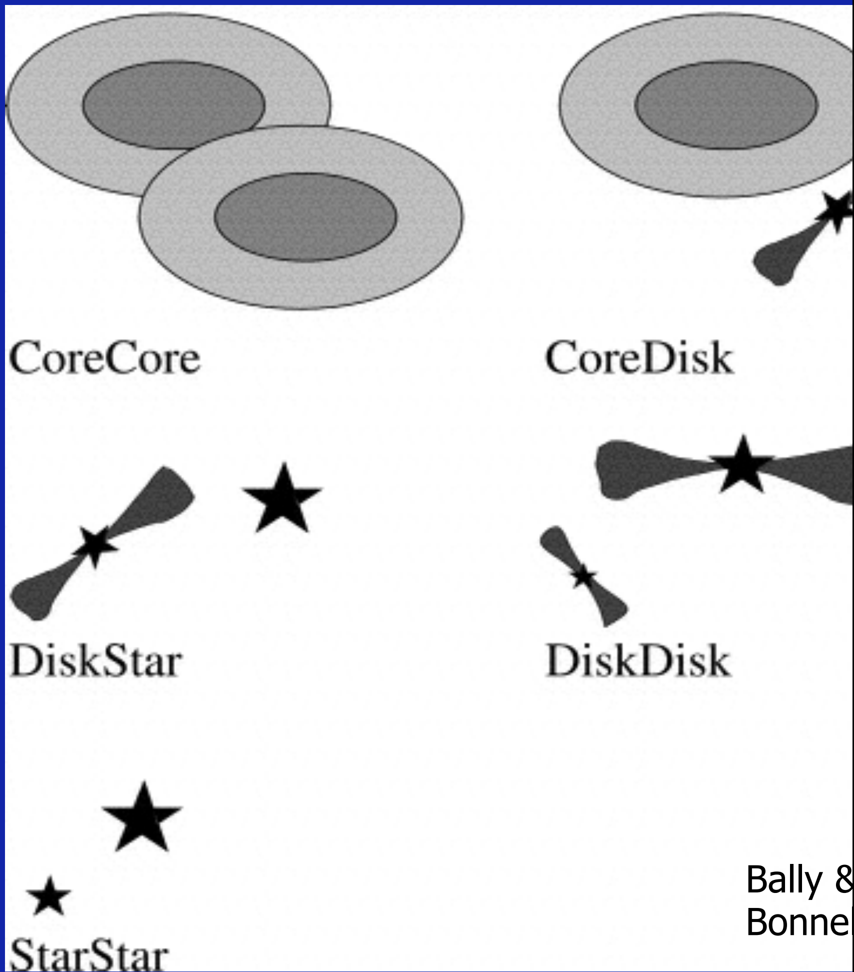
- Gas clump first fragments into large number of cores with approximately a Jeans mass.
  → Hence fragmentation on smaller scales.

- Each clump subsequently accretes gas from the surrounding reservoir.

- Even gas that was originally far away may finally fall onto the protostar.



Coalescence and merging

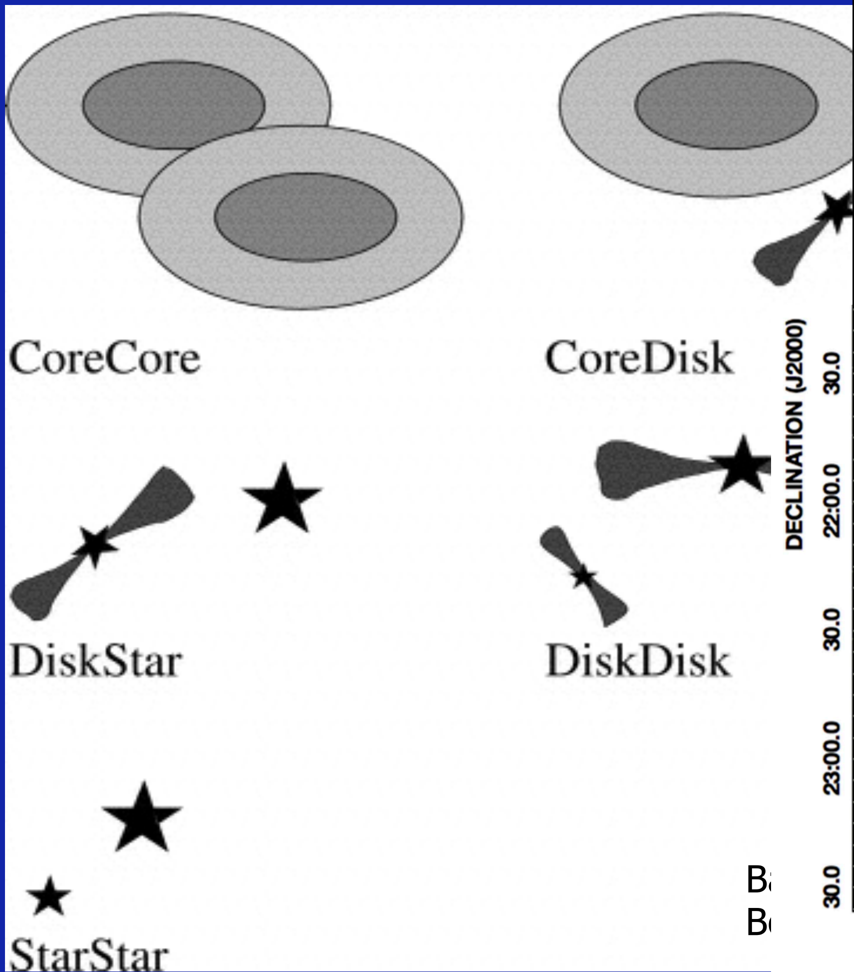


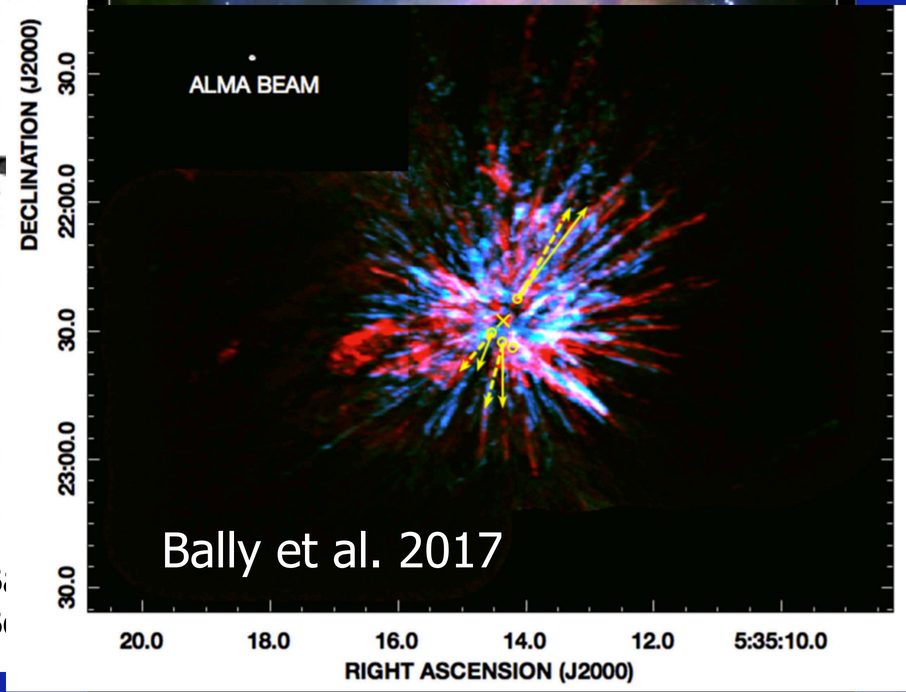
- Required (proto)stellar densities of the order 10^6 to 10^8 stars per pc^3.

- Very explosive events expected.

- Collimated outflows and jets can barely survive.

Coalescence and merging





- Required (proto)stellar densities of the order 10^6 to 10^8 stars per pc^3.

- Very explosive events expected.

- Collimated outflows and jets can barely survive.

Topics today

- General concepts of massive star formation

- Outflows in high-mass star-forming regions

- Rotation and disks

- Clusters and the IMF

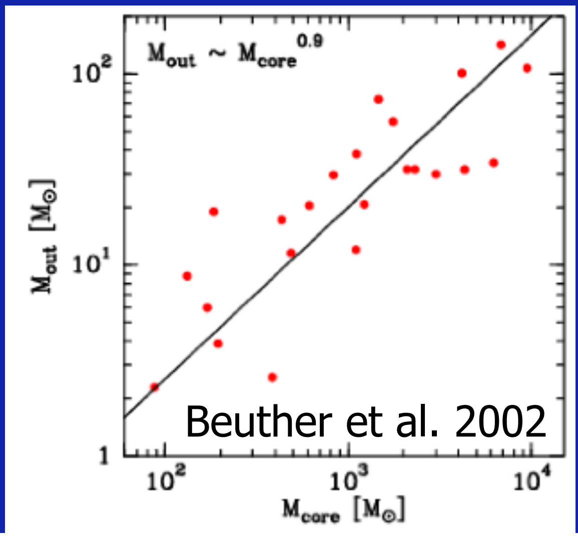
Single-dish maps of massive outflows

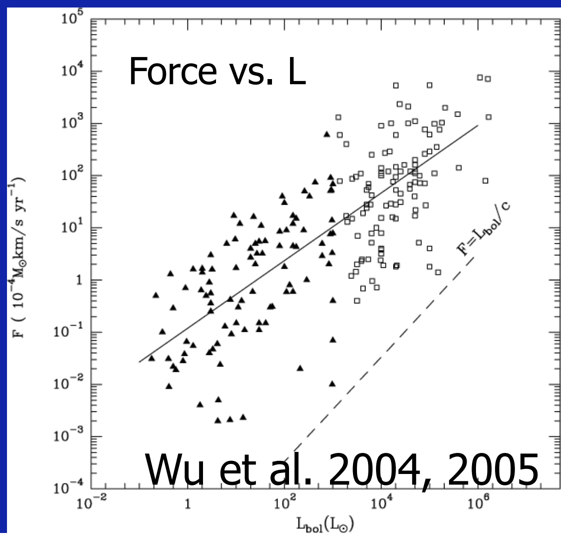
- Early observations claimed different collimation degrees for massive outflows.
  → different formation? → See high resolution image on next slide

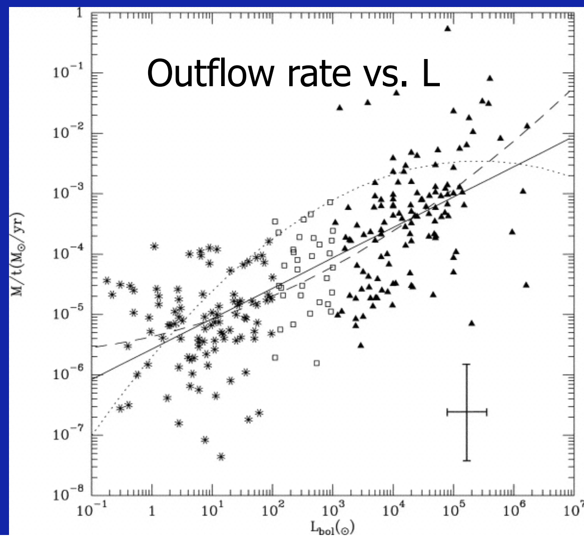
- Outflow-mass scales with core mass.

- Outflow force implies non-radiative outflow driving.

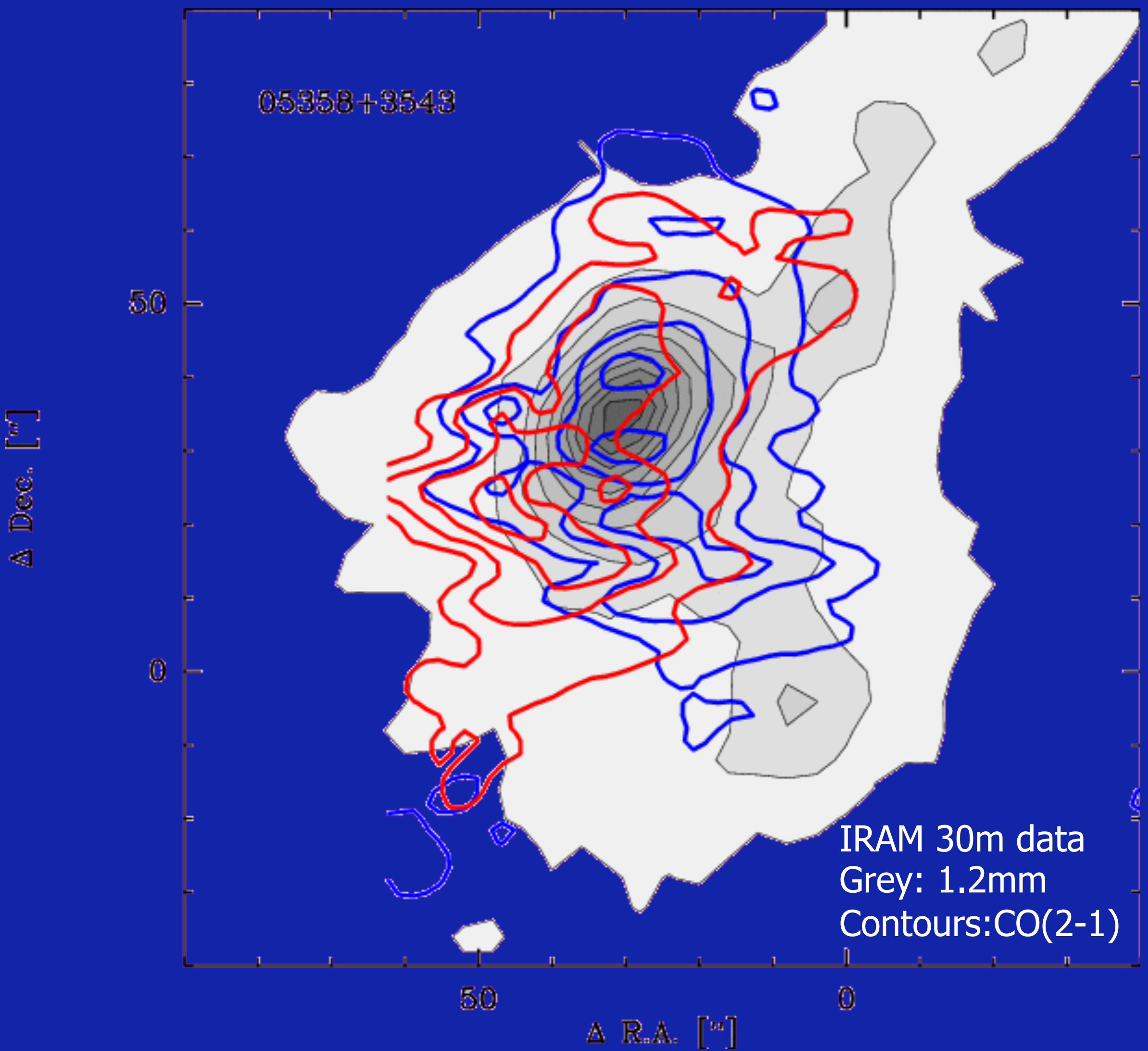
- High outflow rates imply high accretion rates.





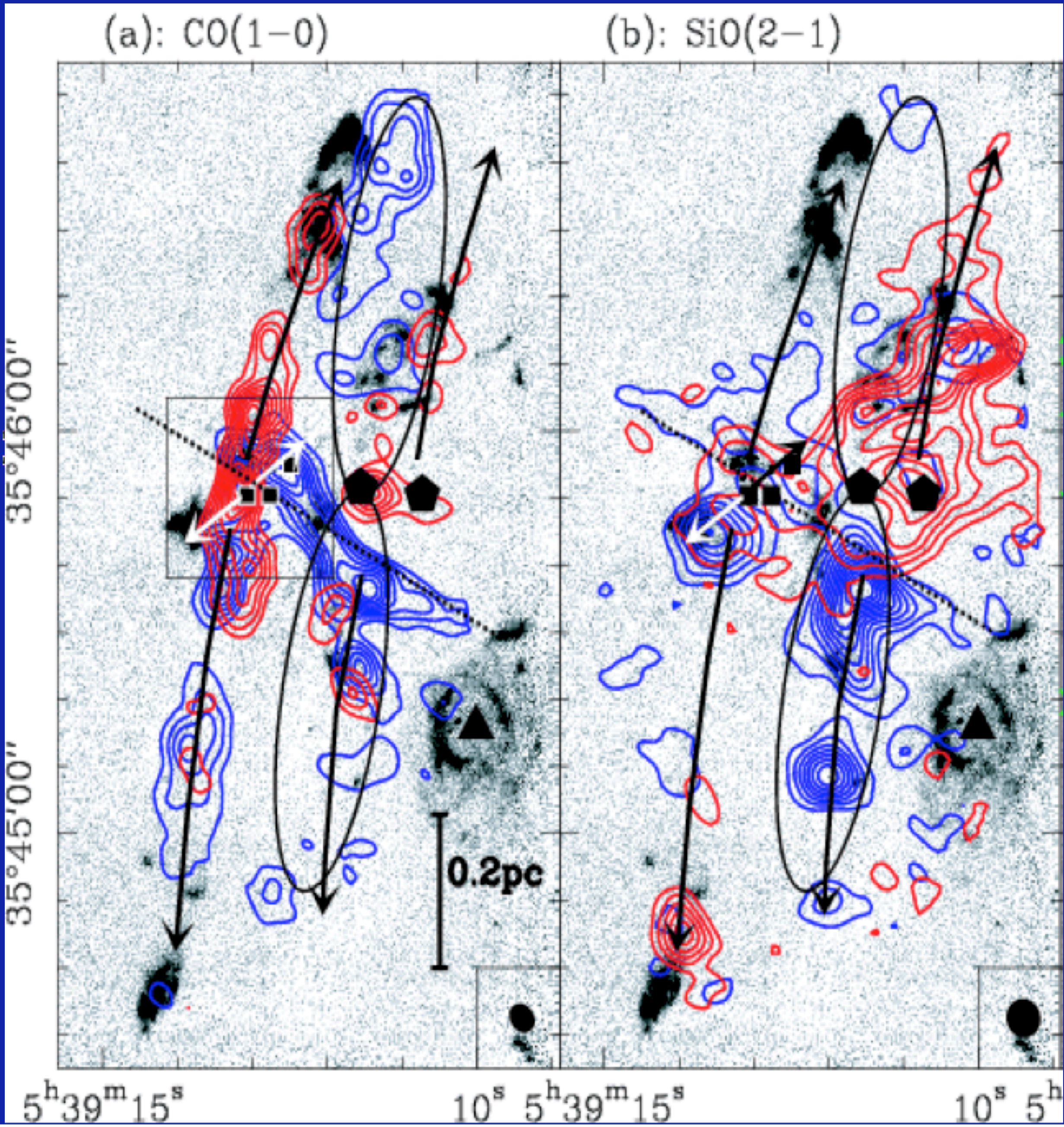


Collimated massive jets and outflows



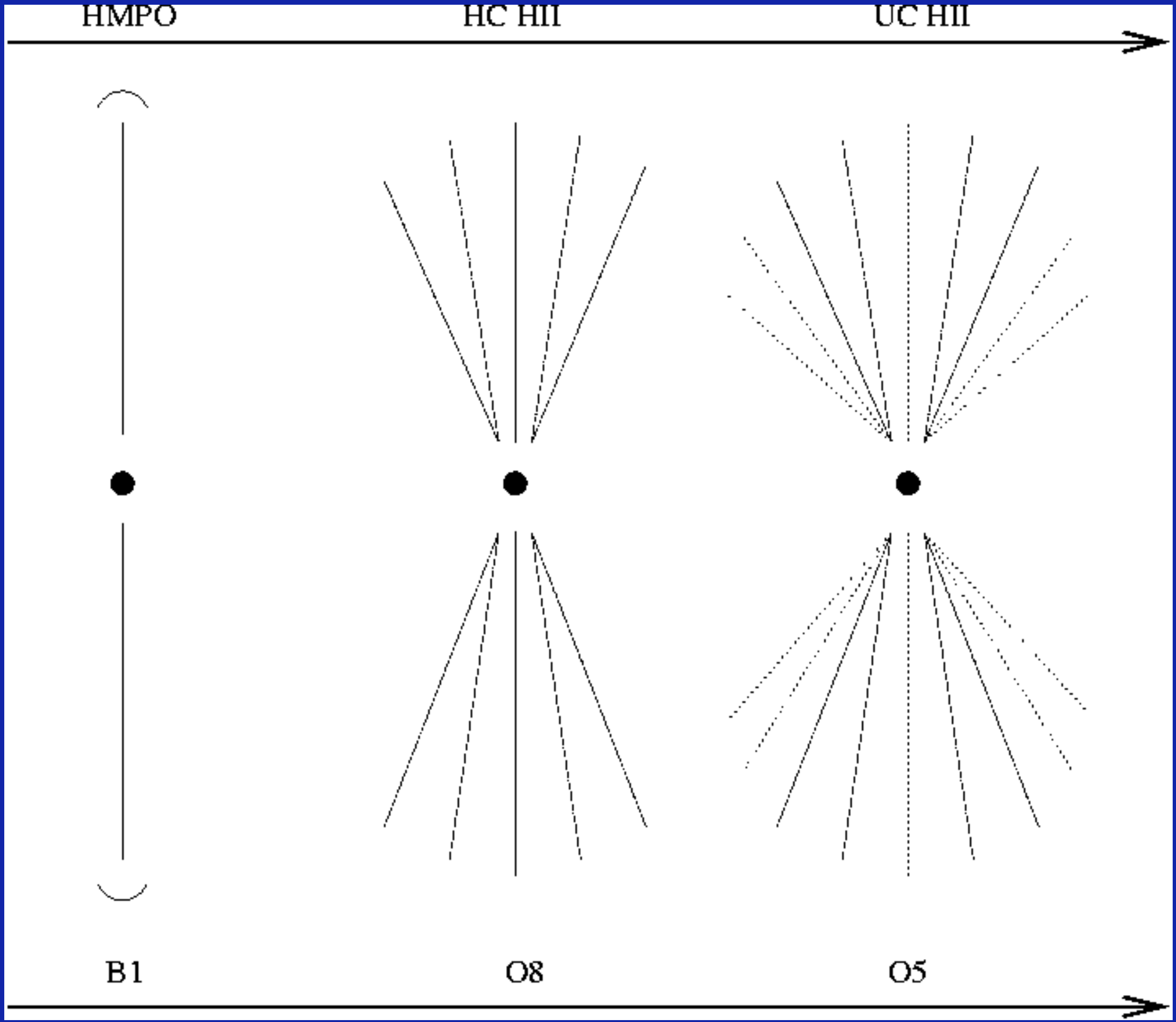
Beuther et al. 2002

Collimated massive jets and outflows



Beuther et al. 2002

An evolutionary scenario



Beuther & Shepherd 2005

- Outflows are ubiquitous phenomena
- Jet-like outflows exists at least up to early-B and late-O-type stars.
- The observations suggests an evolutionary scenario.

Topics today

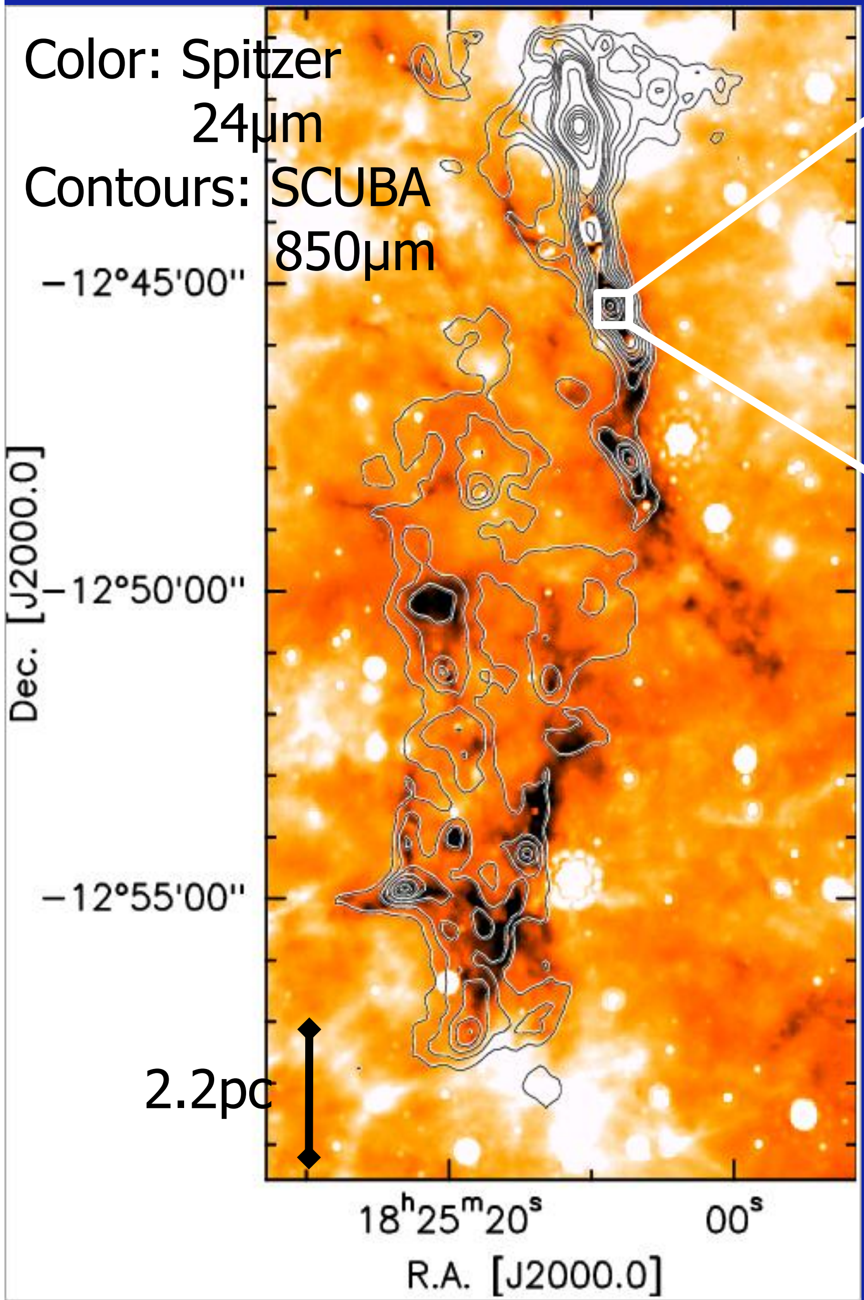
- General concepts of massive star formation

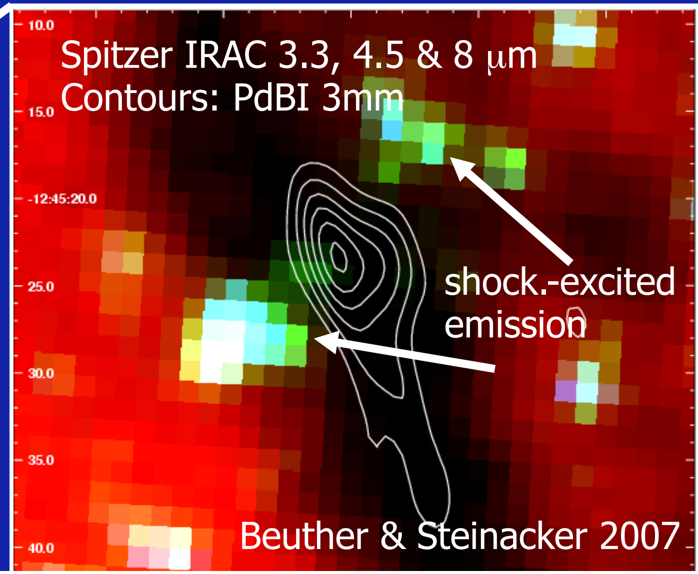
- Outflows in high-mass star-forming regions

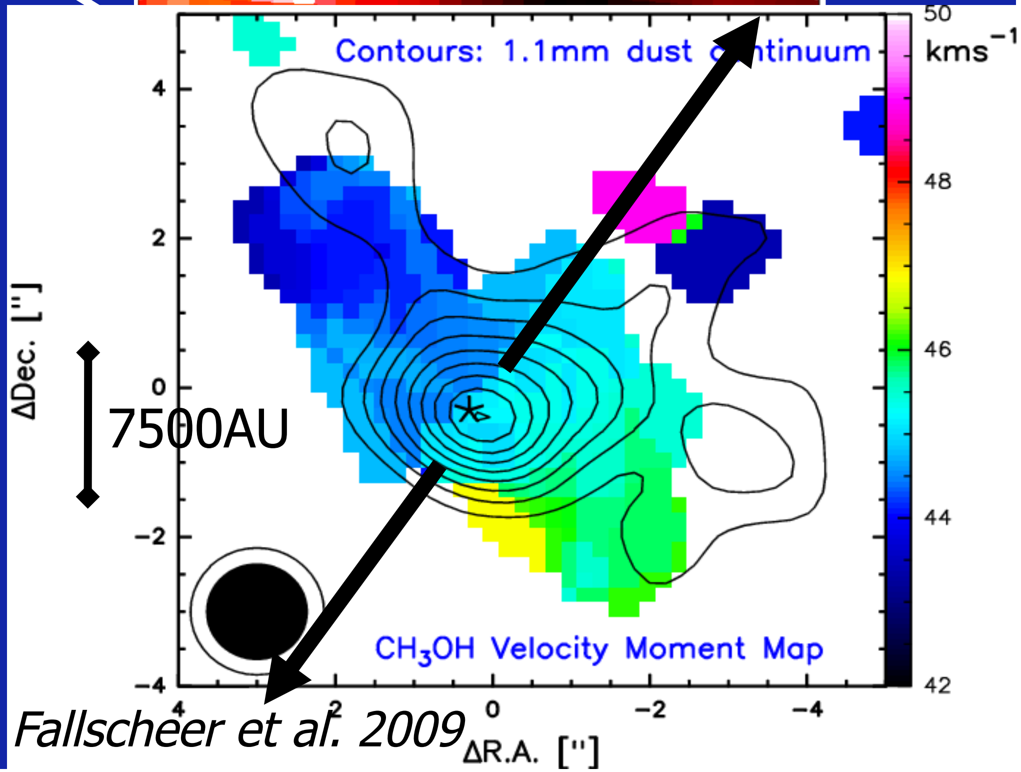
- Rotation and disks

- Clusters and the IMF

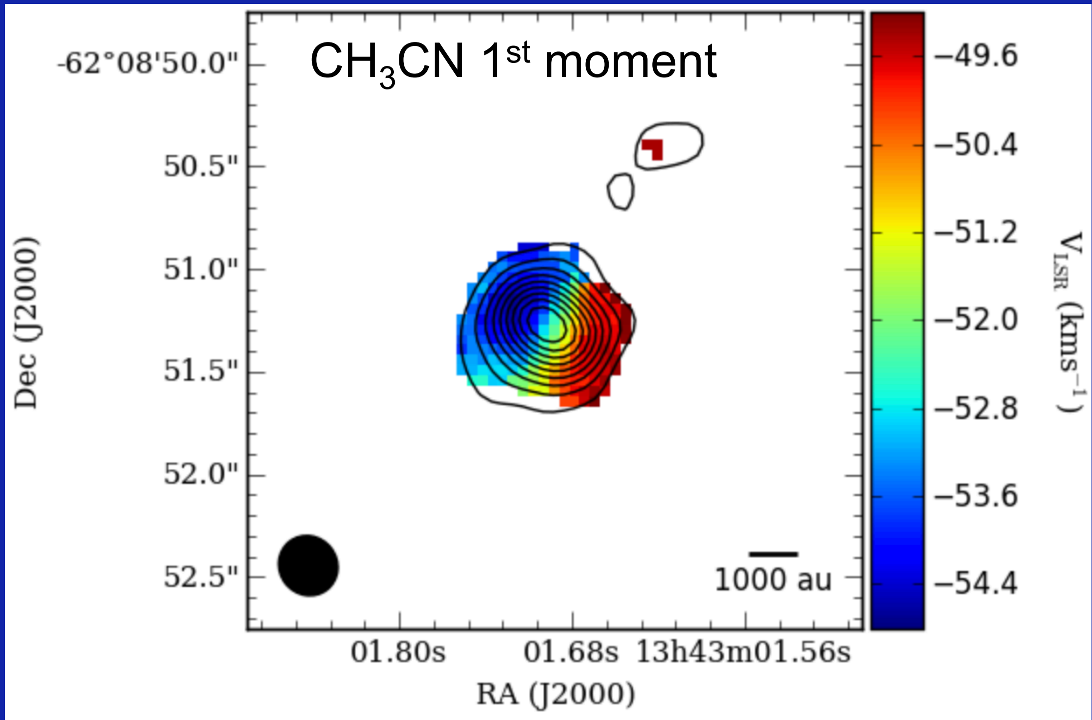
Rotation at the earliest evolutionary stages

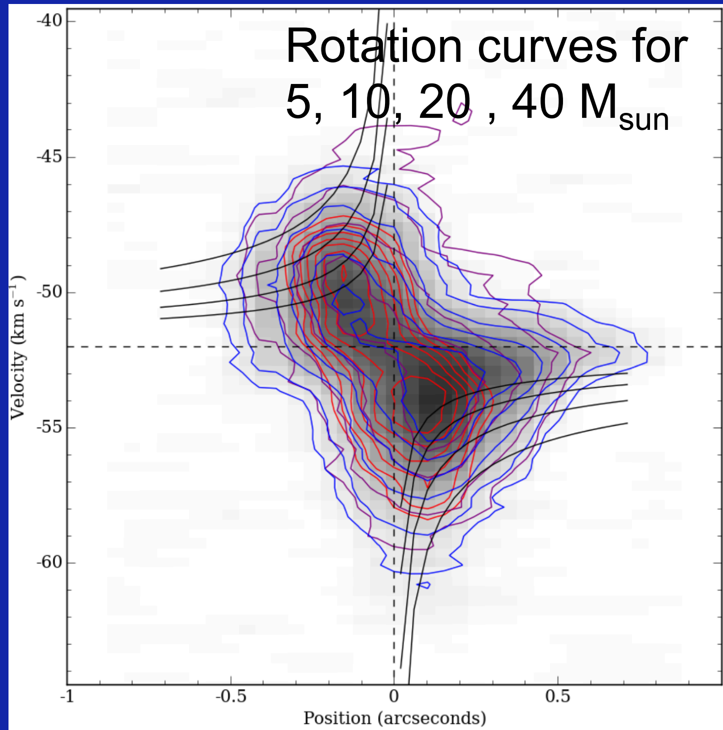






ALMA observations of AFGL4176

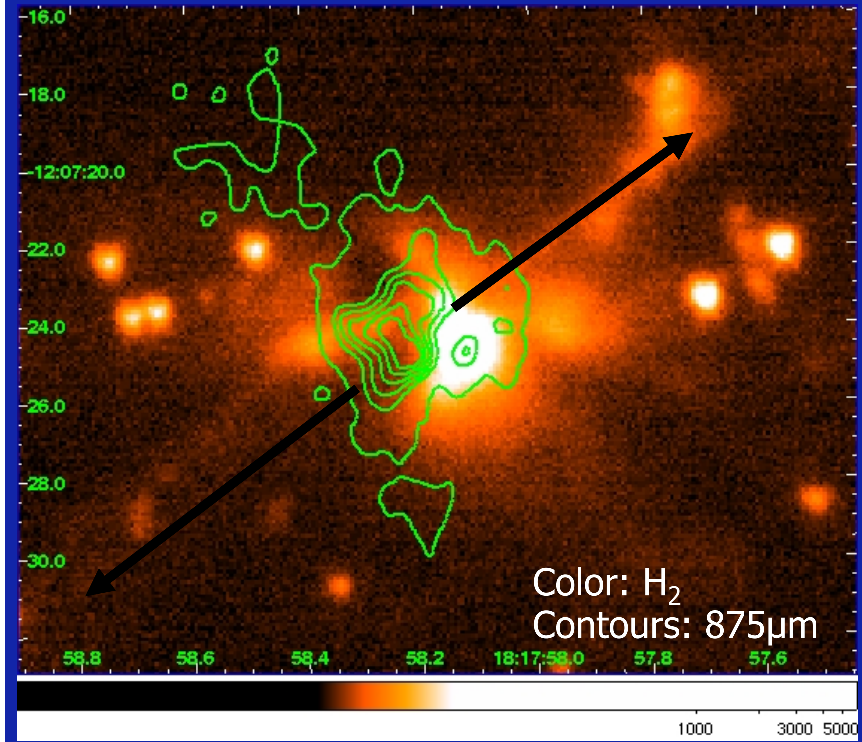


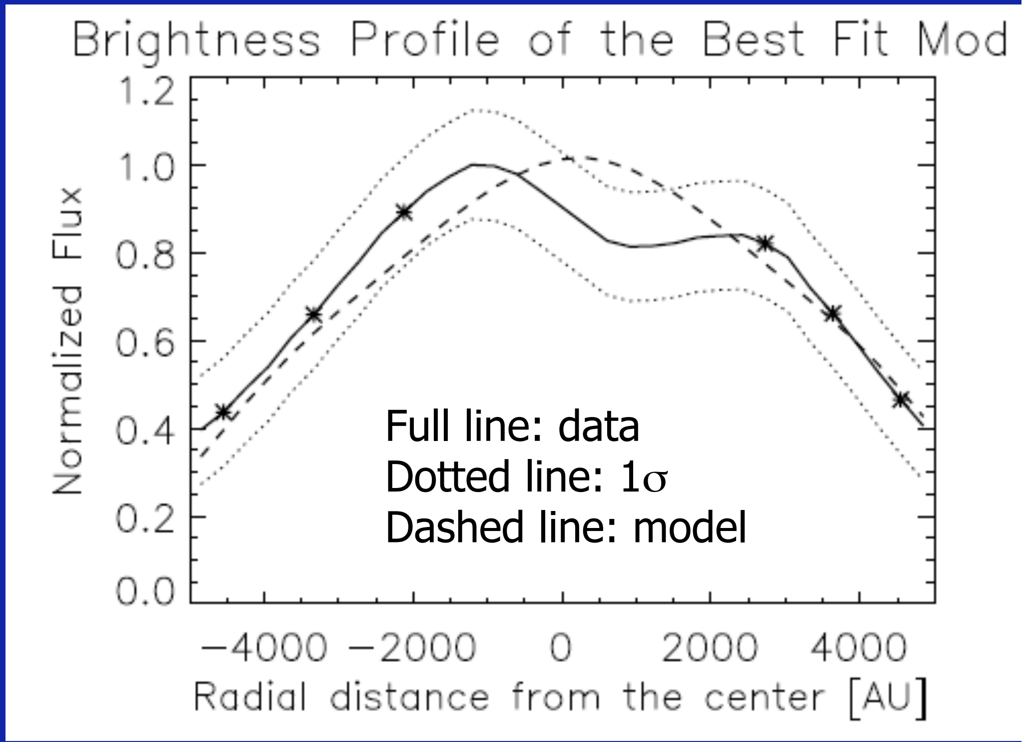


Best fit for Keplerian disk around $25M_{sun}$ star

Johnston et al. 2015

Disk structure from dust continuum emission





- Dust lane perpendicular to outflow, diameter roughly 6000 AU.

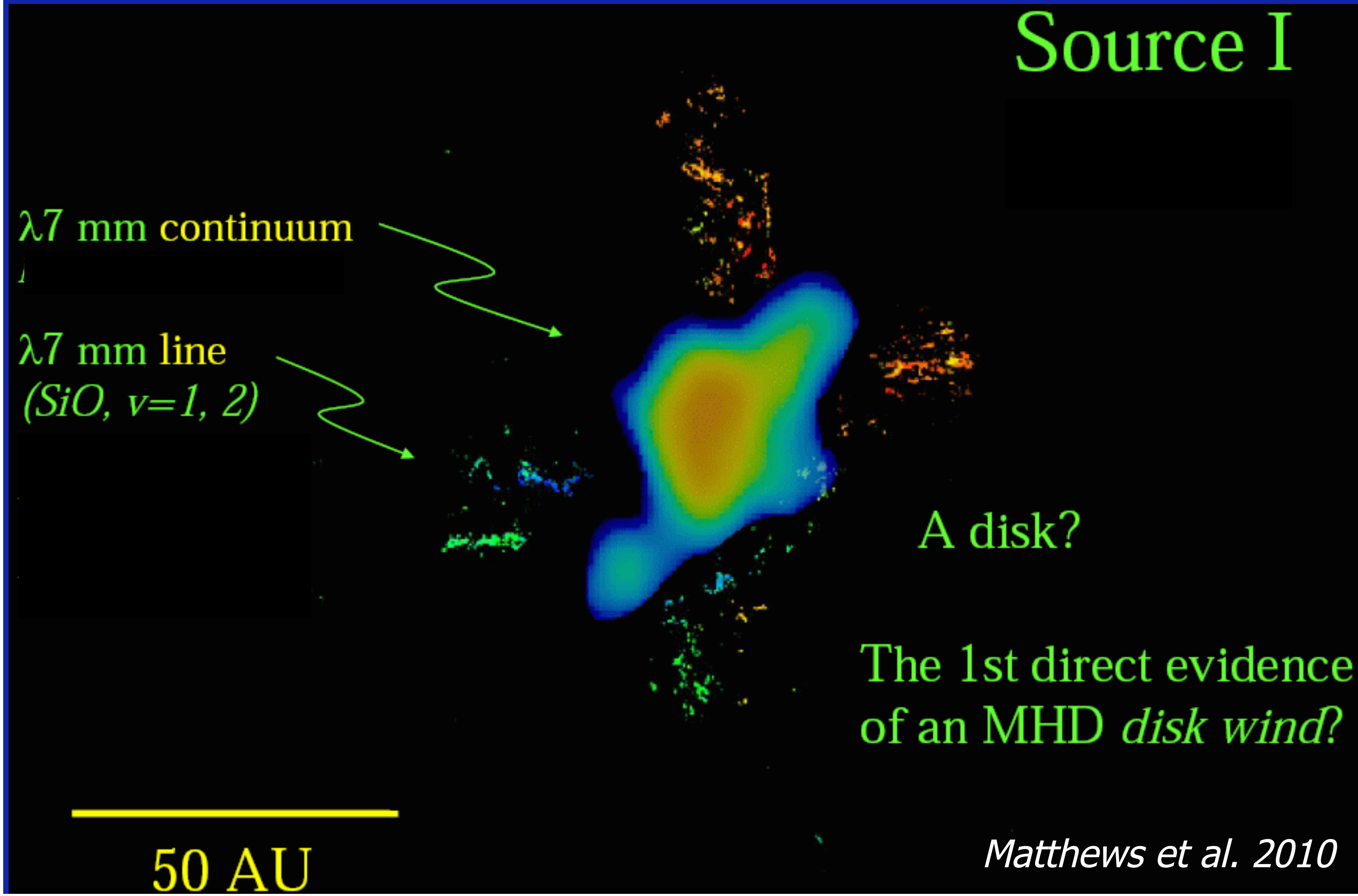
- Model comparison with low-mass disks:

→ Quantitative parameters like mass and size exceed low-mass disks by orders of mag.

→ Qualitative parameters like density profile and disk flaring profile agree well.

Fallscheer et al. 2011

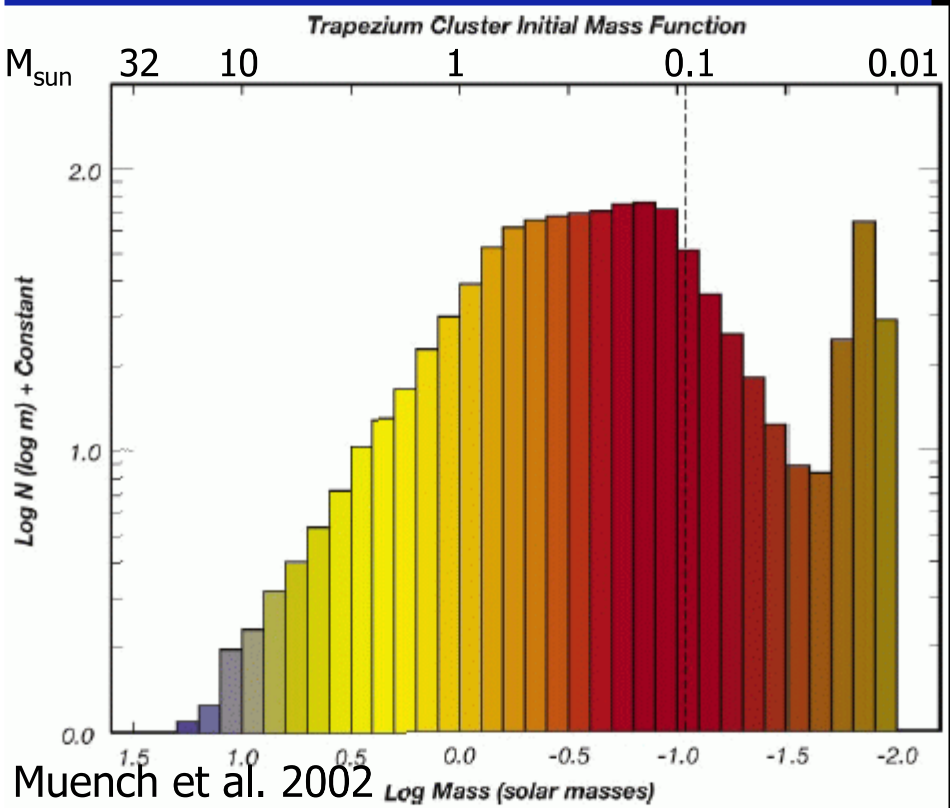
The disk-outflow system in Orion-source I

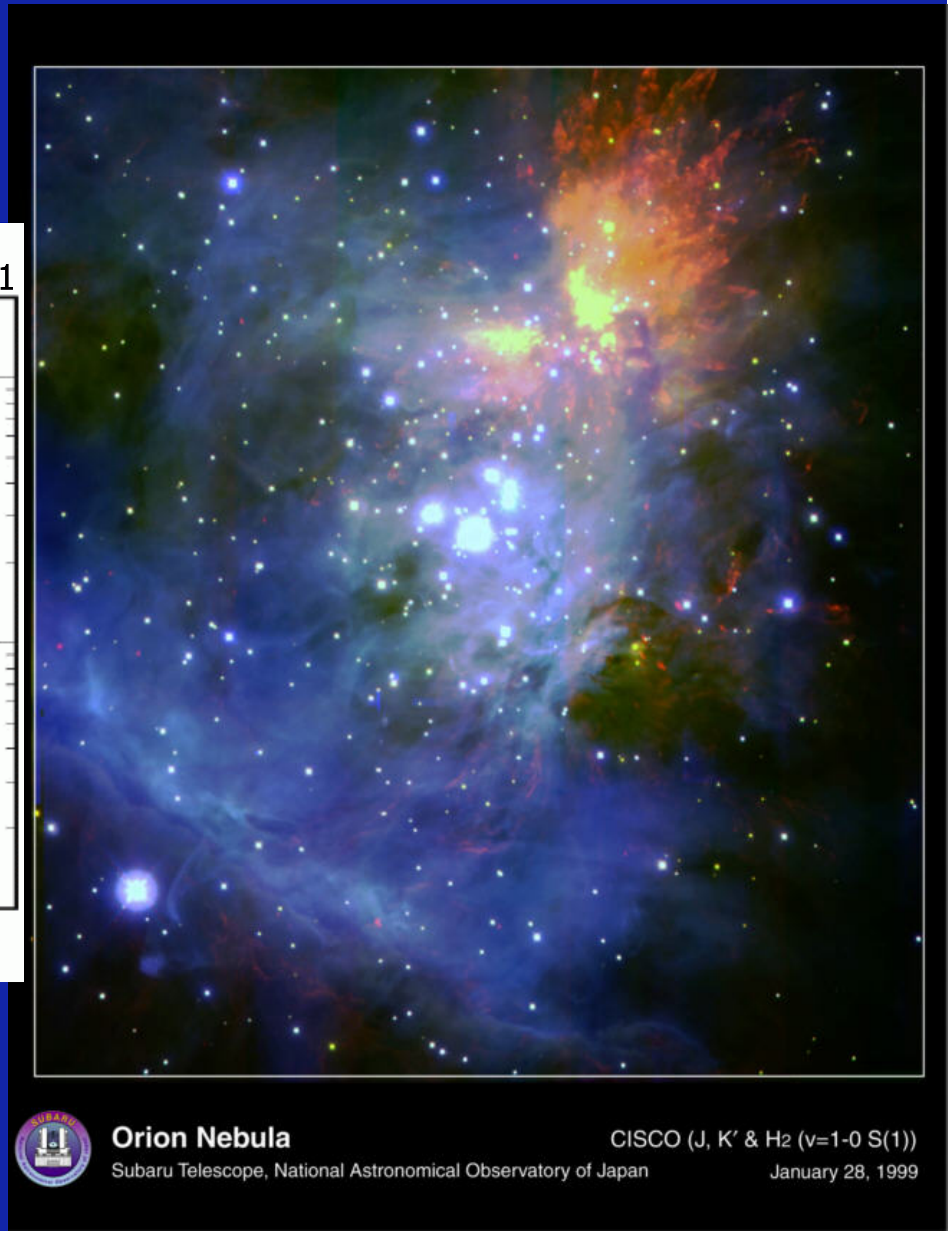


Topics today

- General concepts of massive star formation
- Outflows in high-mass star-forming regions
- Rotation and disks
- Clusters and the IMF

Clusters and the Initial Mass Function (IMF)





General properties of the IMF

- Almost all stars form in clusters, isolated star formation is exception.

- Seminal paper 1955 by E. Salpeter: linear: $dN/dM \sim M^{-2.35}$ *(M > 1Msun)*
  log: $d(\log N)/d(\log M) \sim (\log M)^{-1.35}$

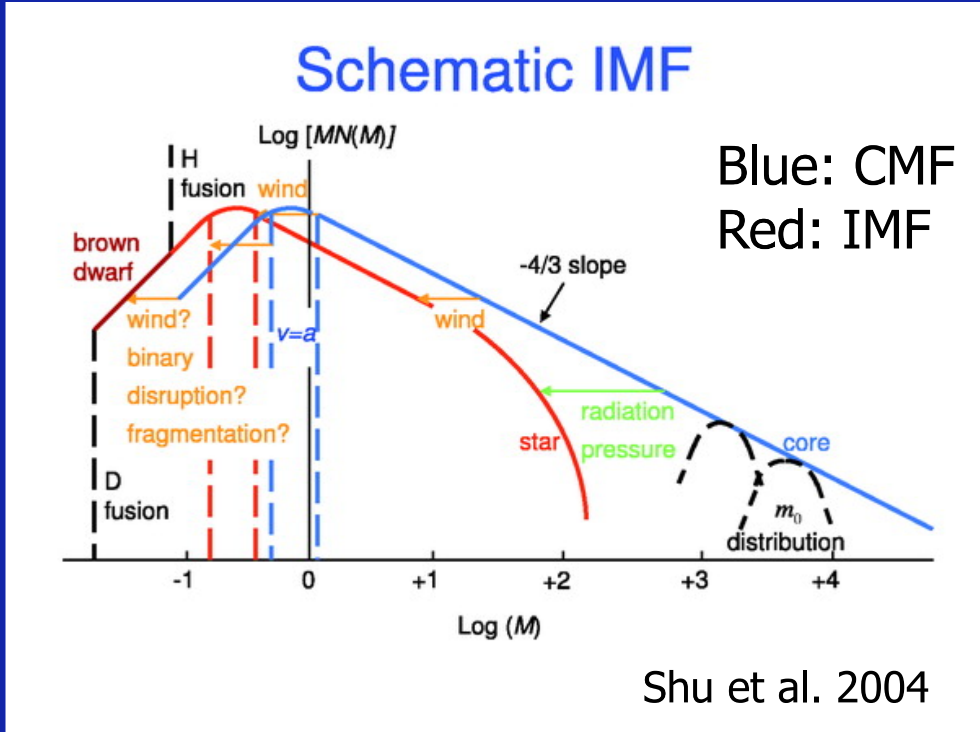
- More detailed description of the total IMF (e.g., Kroupa 2001): $dN/dM \sim M^{-a}$
  $a = 0.3 \rightarrow 0.01 \leq M/M_{sun} \leq 0.08$ (brown dwarf regime)
  $a = 1.3 \rightarrow 0.08 \leq M/M_{sun} \leq 0.5$
  $a = 2.3 \rightarrow 0.5 \leq M/M_{sun}$

- Or lognormal (Chabrier 2003)

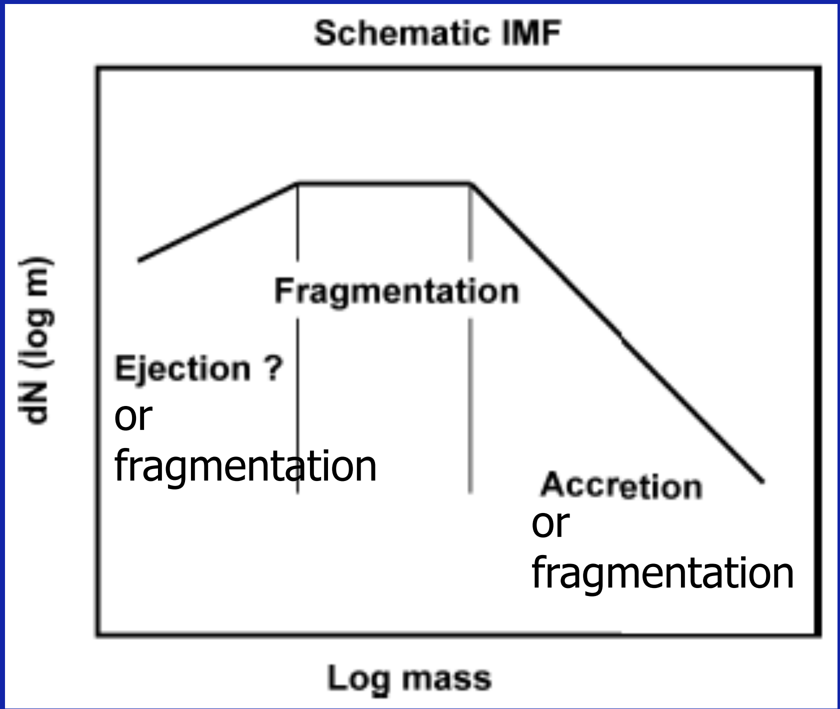
- Characteristic mass plateau around 0.5 M_{sun} (see mol. cl. lect.)

- Upper mass limit of ~ 150M_{sun}

- Largely universally valid, in clusters and the field in our Galaxy and extragalactic systems.



General properties (maybe) governing the IMF



- Mass plateau likely due to original fragmentation and thermal physics.

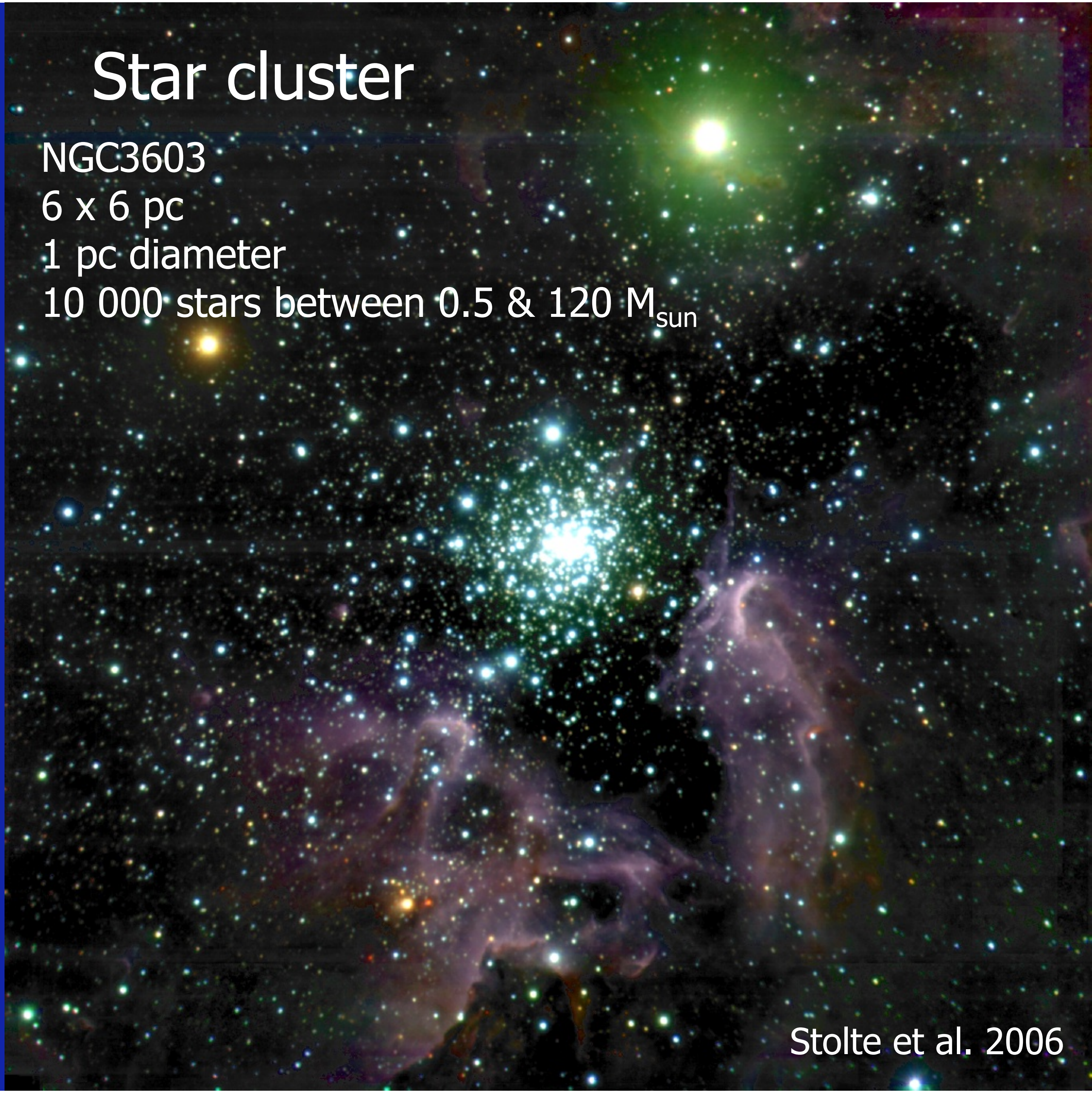
- At low-mass end, fragmentation may not be efficient enough and dynamical ejection could help.

- Are large, massive fragments stable enough to be responsible for the Salpeter tail of the IMF, or do large clumps further fragment so that later competitive accretion may set the masses of the high-mass end?
  - -- Initially, one would expect fragmentation down to the original Jeans-mass at the beginning of collapse.
  - -- However, early accretion luminosity may heat the surrounding gas relatively far out → This would increase the Jeans-mass and inhibit further fragmentation.

    → Not finally solved yet!

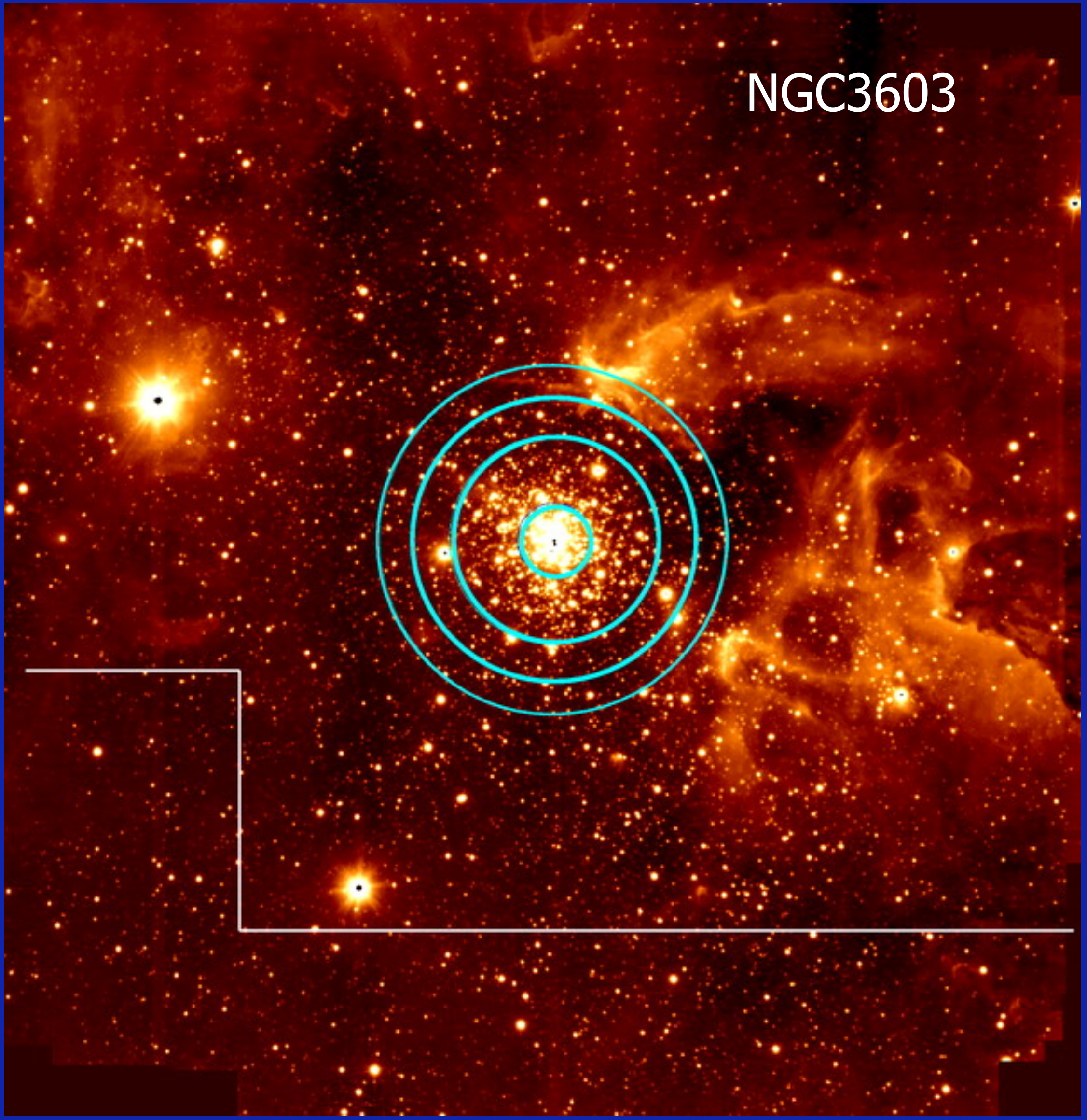
Star cluster

NGC3603
6 x 6 pc
1 pc diameter
10 000 stars between 0.5 & 120 M_{sun}



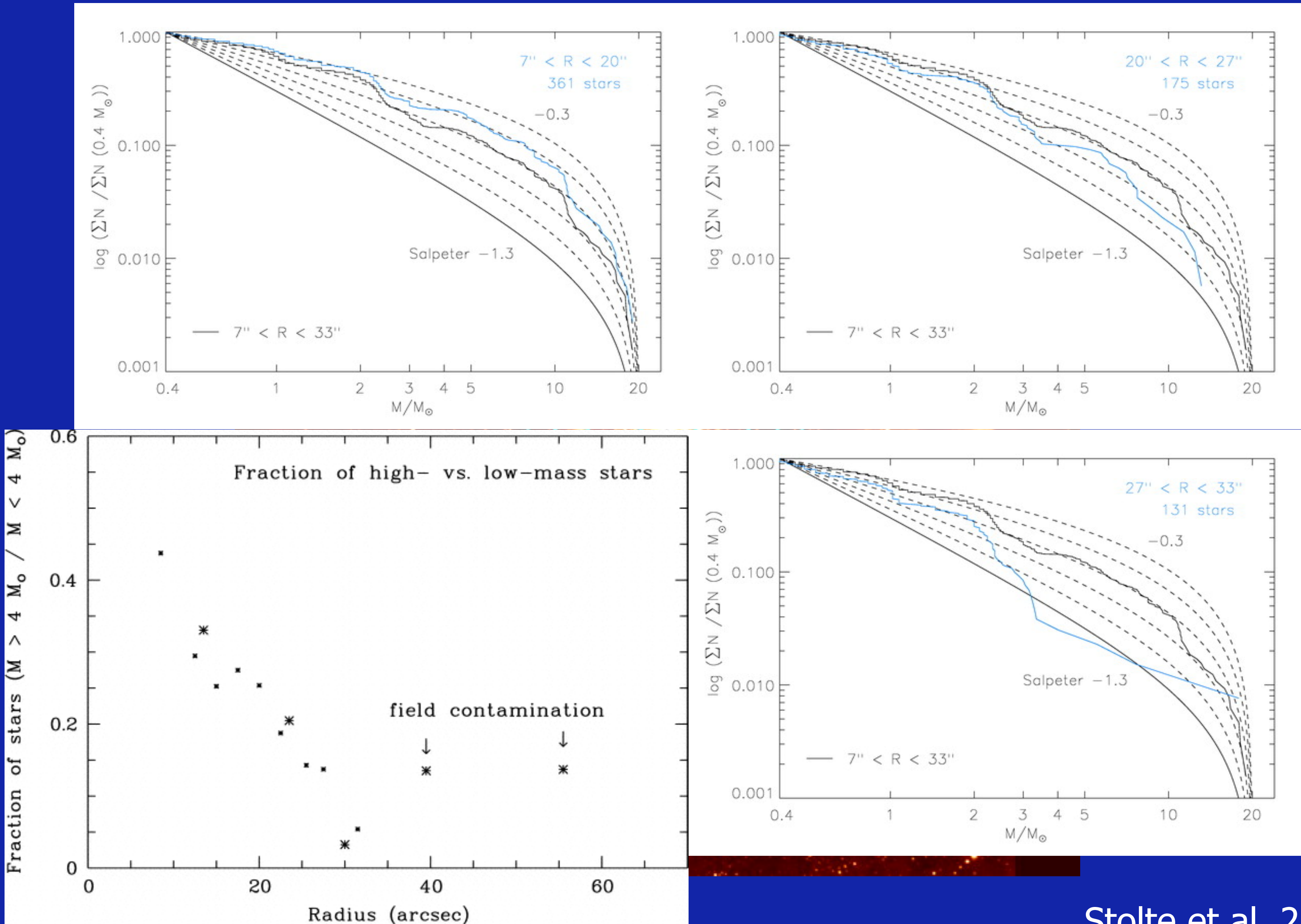
Stolte et al. 2006

Mass segregation



Stolte et al. 2006

Mass segregation



Stolte et al. 2006

Summary

- Massive stars are very important for energy budget and nucleosynthesis.

- They form exclusively in a clustered mode.

- They have very short Kelvin-Helmholtz contraction times and hence no optically observable pre-main sequence evolution.

- Large radiation pressure has to be overcome.

- Two main proposals: (1) scale up low-mass star formation scenario (turbulent core model) with accretion disks and enhanced accretion rates. (2) Turn more dynamical, competitive accretion, coalescence and merging.

- Likely a combination of turbulent core and competitive accretion is solution.

- No real evidence for coalescence and merging. Seems not necessary but may exist is selected sources.

- Discussed outflows, disks and clusters.

Sternentstehung - Star Formation

Winter term 2017/2018

Henrik Beuther & Thomas Henning

17.10 Today: Introduction & Overview (H.B.)
24.10 Physical processes I (H.B.)
31.10 no lecture – Reformationstag
07.11 Physcial processes II (H.B.)
14.11 Molecular clouds as birth places of stars (H.L.)
21.11 Molecular clouds cont., virial & Jeans Analysis (H.B.)
28.11 Collapse models I (H.B.)
05.12 Collapse models II (T.H.)
12.12 Protostellar evolution (T.H.)
19.12 Pre-main sequence evolution & outflows/jets (T.H.)
09.01 Accretion disks I (T.H.)
16.01 Accretion disks II (T.H.)
23.01 High-mass star formation, clusters and the IMF (H.B.)
30.01 Planet formation (T.H.)
06.02 Examination week, no star formation lecture

Book: Stahler & Palla: The Formation of Stars, Wileys

More Information and the current lecture files: http://www.mpia.de/homes/beuther/lecture_ws1718.html

beuther@mpia.de, henning@mpia.de